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THESIS

SHALLOW WATER AMBIENT NOISE CAUSED BY BREAKING WAVES IN THE SURF ZONE

by

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December, 1994

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Omnidirectional ambient noise measurements acquired in Monterey Bay, California were applied with modelled Transmission Loss (TL) to calculate the spectral source level of surf-generated noise. A full geoacoustic model of the coastal environment was assembled and used in the Finite Element Parabolic Equation propagation loss model to obtain transmission loss values for this calculation. A uniform 12.5 km linear effective source length was assumed. Estimates of wind and wave noise were subtracted from observed levels to determine the contribution due to surf.

TL estimates show that surf noise propagation has some dependence on the geoacoustic environment and on frequency. At 300 Hz a 5 dB difference was noted between estimated TL 5 km from the Ft. Ord beach and estimated TL 5 km from the Pt. Pinos beach. At 500 Hz, the difference along these paths was reversed. TL is particularly affected by the first 2 km of interactions with the sea bed. A difference of 10-15 dB was noted between estimated TL across a uniformly granitic sea bed with a given slope and estimated TL for a sea bed of the same slope with 2 m of sediment overlying moderately fast bedrock. The source level densities for heavy surf at Ft. Ord beach were estimated to be 129, 118, 114, and 102 dB ref. 1 micro-Pa/Hz$^{1/2}$/m at 1 m for 50, 300, 500, and 1000 Hz respectively. The estimated pressure spectrum level due only to heavy surf breaking on the Ft. Ord beach was comparable to typical pressure spectrum levels in deep water due to distant heavy shipping and wind and wave noise at high wind speeds. At 300 Hz, the pressure spectrum level 8.5 km from the beach due to breaking surf was 81 dB ref. 1 micro-Pa/Hz$^{1/2}$ during heavy surf conditions. The pressure spectrum level 3.2 km from the beach due to breaking surf was 70 dB ref. 1 micro-Pa/Hz$^{1/2}$ during low surf conditions. The pressure spectrum level of the heavy shipping contribution to deep water ambient noise is 70 dB and that of 50 kt winds is 76 dB. Surf noise at 300 Hz appears to account for 86% of the measured ambient noise intensity at 8.5 km from the beach during heavy surf conditions and 94% of the measured ambient noise intensity at 3.2 km from the beach during light surf conditions. Surf spectral source level represents a transportable property which may be applied in computing ambient noise levels in other littoral regions.

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SHALLOW WATER AMBIENT NOISE CAUSED BY BREAKING WAVES IN THE SURF ZONE

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Omnidirectional ambient noise measurements acquired in Monterey Bay, California were applied with modelled Transmission Loss (TL) to calculate the spectral source level of surf-generated noise. A full geoacoustic model of the coastal environment was assembled and used in the Finite Element Parabolic Equation propagation loss model to obtain transmission loss values for this calculation. A uniform 12.5 km linear effective source length was assumed. Estimates of wind and wave noise were subtracted from observed levels to determine the contribution due to surf.

TL estimates show that surf noise propagation has some dependence on the geoacoustic environment and on frequency. At 300 Hz a 5 dB difference was noted between estimated TL 5 km from the Ft. Ord beach and estimated TL 5 km from the Pt. Pinos beach. At 500 Hz, the difference along these paths was reversed. TL is particularly affected by the first 2 km of interactions with the sea bed. A difference of 10-15 dB was noted between estimated TL across a uniformly granitic sea bed with a given slope and estimated TL for a sea bed of the same slope with 2 m of sediment overlying moderately fast bedrock. The source level densities for heavy surf at Ft. Ord beach were estimated to be 129, 118, 114, and 102 dB ref. 1 micro-Pa/Hz$^{1/2}$/m at 1 m for 50, 300, 500, and 1000 Hz respectively. The estimated pressure spectrum level due only to heavy surf breaking on the Ft. Ord beach was comparable to typical pressure spectrum levels in deep water due to

distant heavy shipping and wind and wave noise at high wind speeds. At 300 Hz, the pressure spectrum level 8.5 km from the beach due to breaking surf was 81 dB ref. 1 micro-Pa/Hz$^{1/2}$ during heavy surf conditions. The pressure spectrum level 3.2 km from the beach due to breaking surf was 70 dB ref. 1 micro-Pa/Hz$^{1/2}$ during low surf conditions. The pressure spectrum level of the heavy shipping contribution to deep water ambient noise is 70 dB and that of 50 kt winds is 76 dB. Surf noise at 300 Hz appears to account for 86% of the measured ambient noise intensity at 8.5 km from the beach during heavy surf conditions and 94% of the measured ambient noise intensity at 3.2 km from the beach during light surf conditions. Surf spectral source level represents a transportable property which may be applied in computing ambient noise levels in other littoral regions.

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I. INTRODUCTION

A. OBJECTIVES

Acoustic energy propagation in the littoral ocean environment is more complex than it is in the deep ocean. Sound waves travelling in shallow water suffer multiple bottom/sub-bottom interactions with a highly variable, and sometimes lossy, range dependent bottom/sub-bottom. On the other hand, at short ranges (0 to 15 km), the loss due to bottom interaction in shallow water is counter balanced by reduced spreading loss near the source. Further complexity is added because the water column sound speed profile, volume absorption, and the scattering and refraction characteristics of the ocean surface, the bottom, and the sub-bottom may also be range dependent. The ambient noise and reverberation may be highly variable due to both propagation effects and variability of dominant noise sources and bottom reflections. The water column sound speed profile may be highly time dependent as well.

The recent shift of the U.S. Navy emphasis away from blue water theaters of operation has focussed considerable scientific exploration to discover answers to the many questions surrounding shallow water acoustic energy propagation. A particular littoral water phenomenon neither well understood nor researched is "surf point noise," an expression coined perhaps by the submarine force, which describes surf-generated broadband noise that propagates from unique surf zones, with apparently little Transmission Loss (TL), dozens of kilometers to sea. As the name implies, prominent coastal headlands may be a source of some surf point noise. Other coastline types, such as long beaches parallel to the direction of surf wave fronts, may generate surf noise that propagates seaward as discovered by Wilson et al. (85). Wilson cited earlier reports by Knudsen et al. (48), Bardyshev et al. (73), and Zakharov and Rezhevkin (74) which document seaward propagation of surf-generated noise. That broadband energy from 1-1000 Hz should escape the ruthless scattering, absorption, and bottom attenuation of the shallow water region in the vicinity of the surf zone and propagate dozens of kilometers to sea is the mystery of surf point noise. The expectation was that the propagation loss from the breaking wave source at the shore to deeper water was so great that surf generated noise could not be a significant contributor to ocean ambient noise (Saenger, 61). Part of the solution to this mystery may be contained in the significant reduction of the near-source spherical spreading loss typical of deep water environments.

The specific objectives are first to analyze and model the geoacoustic character of the littoral sea bed within Monterey Bay and compute TL from the surf zone, and second, to derive empirically the spectral surf source level per meter of beach (spectral source level density) as a function of sea state using ambient noise data from Monterey Bay (Wilson et al., 85). A discussion of this analysis as is relates to surf *point* noise appears in Chapter V.

Many of the methodologies of this paper were utilized in DUCK-94, an experiment where surf-generated noise were measured along a wide continental shelf environment off the beach at Duck, NC. (Wilson and Paquin, in progress)

B. QUALITATIVE CHARACTERISTICS

Interviews by the author with crewmembers of naval vessels who have encountered surf point noise around the globe revealed some qualitative aspects of the phenomenon. It can be loud enough (>20 dB above background) to cause loss of a submarine contact on broadband sonars. It can also be used to tactical advantage as a noise haven in which submarines and other undersea warfare units may hide. It has often been associated with prominent headlands onto which diffracted wave trains impact but has also been noted to emanate from deep "V-notched" bays. It is reportedly similar to moderate to strong noise produced by a distant merchant ship but without the bearing drift over days of observation and without machinery and blade or shaft lines characteristic of shipping noise. It is distinctly different from squall or heavy rain noise. Although nominally generated during higher sea states, surf point noise has been observed at high latitudes in the relative calm of winter under sea state one conditions, possibly as a result of large swell breaking on the beach.

C. NOISE FIELD CHARACTERISTICS

The analysis of ocean noise fields may be carried out in four parts: (1) Study of the TL from a source to a distant receiver, (2) Study of the spatial (horizontal and vertical) distribution of the noise source, (3) Study of the source directivity pattern, and (4) Study of the effective source level causing the noise.

The premise is that surf point noise is, in fact, produced by breaking surf; that is, it is produced by breaking waves either onto headlands or cuspid beaches (Wilson et al., 85). Breaking waves produce incoherent broadband acoustic energy from a few tens of Hertz to greater than 20 kHz associated with the resonance of tiny air bubbles entrained in sea water (Loewen, 91). Modulation of this energy associated with wave train periodicity may have a frequency of around

0.05 Hz. This is referred to as 'surf beat' (Guza and Thornton, 85) That the specific spectral characteristics and source level of noise generated by breaking waves in the surf zone are variable is discussed by several authors, e.g., Kennedy and Glegg (92), Carey and Fitzgerald (93), and Hollett (94) who analyzed <u>breaking</u> wave noise spectra in the open ocean. Spectral characteristics depend on the size and character of the breaking waves which are, in turn, determined by both the variable bottom across the surf zone and by the structure of the <u>arriving</u> waves. Wave structure depends on wind speed, fetch, and the extent of wave interaction.

On a macroscale, headlands concentrate wave energy through diffraction and therefore might be expected to radiate surf-generated noise more strongly than adjacent beaches. Furthermore, the bottom slope leading onto headlands is often steep which might permit the escape of acoustic energy with fewer attenuating bottom interactions than with more gently sloped shorelines. On the other hand, waves breaking on long cusp-shaped beaches might also be loud sources. Here, the integration of spectral source intensity along many kilometers of beach would comprise an effectively large source due to the physical extent of the surf noise generating area.

The sound pressure level of surf point noise dozens of kilometers to sea is a function of both the effective source level and the TL. TL may be relatively low in certain unique nearshore ocean sub-bottom environments. Environmental factors which should support reduced TL near a surf zone include steep bathymetry seaward from the surf zone; an upward refracting sound speed profile in the water column; an upward refracting sediment layer; a fast, smooth reflective bottom; low sediment, sub-bottom, and water column attenuation; and a smooth ocean surface. These factors reduce the incidence and severity of boundary interactions and tend to couple energy that penetrates the bottom back into the water column.

The transmission loss from sound sources near shore to points at sea must be affected by the surface roughness and air bubble entrainment due to the surf and breaking waves. Consideration of these effects could not be made here since currently available TL models do not provide for it.

D. OUTLINE

The next chapter of this paper describes the primary environment examined, Monterey Bay. It also provides a description of models and references used.

Chapter III describes the development of geoacoustic data bases for various paths in Monterey Bay. It provides a theoretical assessment of the anticipated TL expected along specific paths. A description of the Finite Element Parabolic Equation (FEPE) propagation loss model and explanation of its use with the geoacoustic model will be presented. Chapter III presents a discussion of the method for computing spectral surf source level density (source level per meter of beach) in Monterey Bay.

Chapter IV presents the results of the TL modelling and calculations of spectral source level density for the Ft. Ord beach. The significance of the results is discussed.

Chapter V summarizes the current research, presents conclusions drawn and their inferences to surf point noise propagation at locations around the globe, and offers recommendations for additional research.

The Appendix discusses the development of a geoacoustic model and TL plots along two paths in what will be referred to as the San Diego Bight. The purpose of modelling TL in the San Diego Bight is to conduct a preliminary analysis of unusual ambient noise events observed periodically during SWELLEX-1, a two week offshore shallow water noise propagation experiment conducted by the Navy Research and Development Division (NRAD) of the Navy Command, Control and Ocean Surveillance Center (NCCOSC) in July 1993 southwest of Pt. Loma, California (Hodgkiss et al., 94). Loud broadband noise levels waxed and waned over a few hours periodically during the experiment, affecting recordings at frequencies from 200 Hz to 750 Hz somewhat uniformly. Interestingly, the noise was modulated with about a 30 s period and a 5-10 dB amplitude oscillation peak to trough. This noise is thought by some to have been caused by croaker fish. An alternate source appears to be swell breaking either in shallow water south of Pt. Loma or along the Silver Strand beach. The discussion is included in this paper as a possible example of surf point noise and as a catalyst for further research of the extensive shallow water ambient noise recorded both during SWELLEX-1 and SWELLEX-3. (Personal communication with Ryan)

Readers interested in the computer software programs used in displaying TL data generated by the FEPE program and in analyzing the time series acoustic data recorded during SWELLEX-1 should contact Professor Oscar B. Wilson or Professor Robert H. Bourke of the Naval Postgraduate School.

II. ENVIRONMENT EXAMINED

A. MONTEREY BAY

Measurements of the surf-generated noise propagating to sea were conducted by Wilson et al. (85). Two experiments were carried out, one in May 1980 and one during March and April 1981. The data from March 1981 and part of the data from April 1981 were used in the current research. During the March 1981 experiments noise field measurements were made using modified versions of the AN/SQQ-53A DIFAR sonobuoy at three locations, Stations 6, 5, and 7 which were, respectively, 2.8, 4.4, and 8.5 km west of the Ft. Ord beach as shown in Figure (1). A similar set of measurements was made during May 1980 and April 1981 between 0.5 and 4.0 km from the Ft. Ord beach. Station 7 measurements, made 8.5 km from the beach in March 1981 and Station D measurements, made 3.2 km from the beach in April 1981, will be used for calculations in Chapter III. The sonobuoy hydrophones were set at 28 m depth (less in shallow water) and multiplexed recordings were made of the signals from the omnidirectional hydrophone, the horizontally disposed pressure gradient sensors, and the magnetic compass in each sonobuoy. Combining the output of the two acoustic sensors yielded a cardioid beam pattern which could be steered by controlling the demultiplexing process. Verification of the direction of the beam compared with the magnetic compass was accomplished by tracking the noise from the research vessel involved in the experiment. Hydrophone outputs were then recorded with the cardioid steered east toward the Ft. Ord beach, west away from the beach, south toward Monterey and Pt. Pinos, and north toward Santa Cruz into the center of the bay. During the recordings it was believed that there was little contribution

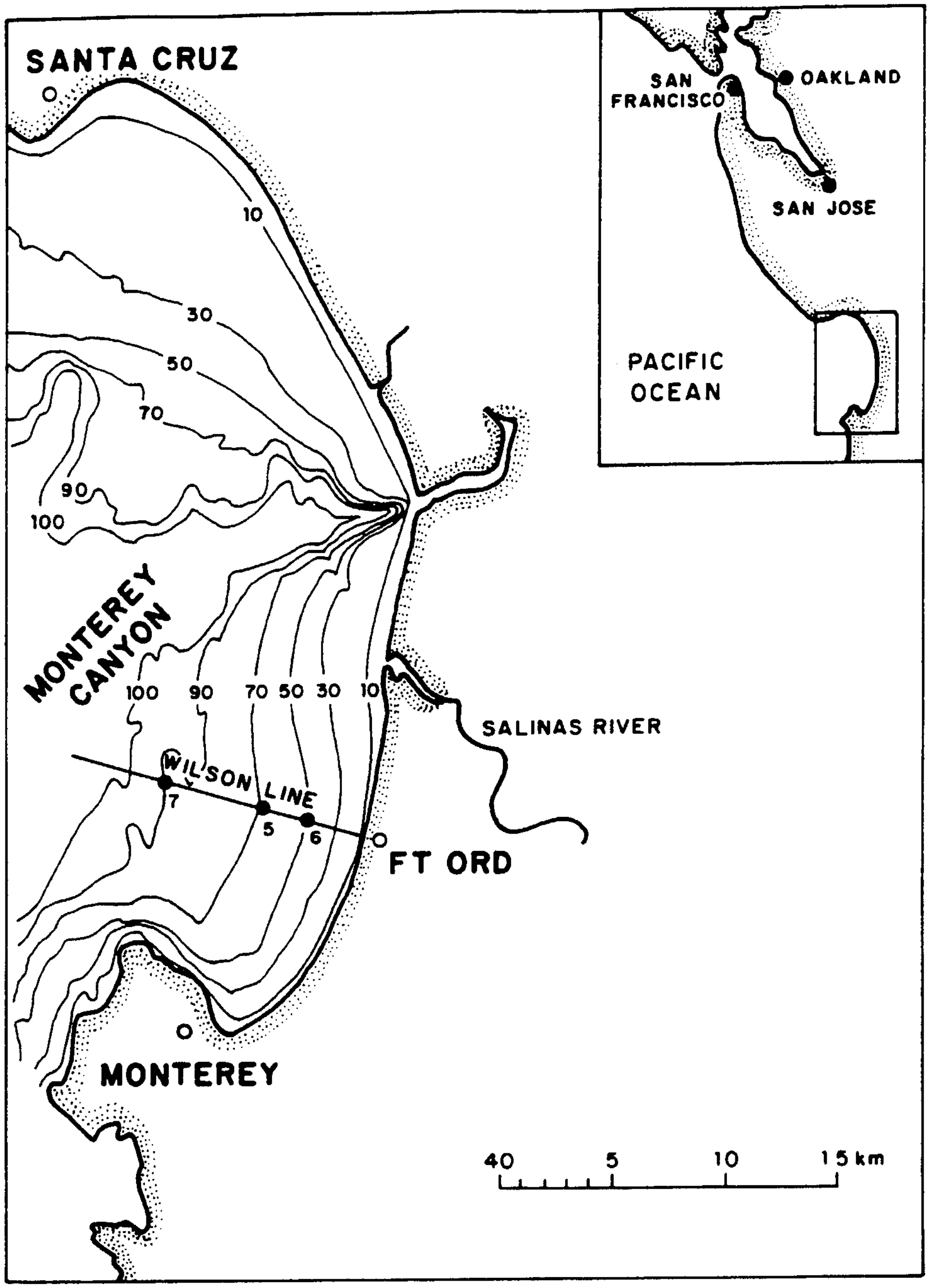

Figure 1. Sites of surf-generated noise measurements made in March 1981 (from Wilson et al., 85). Station 6, 5, and 7 are, respectively, 2.8, 4.4, and 8.5 km from the Ft. Ord beach. Station D, used in April 1981, lies between Stations 5 and 6. Bathymetric contours are in meters. Chart after Chin et al. (88).

to the measured ambient noise from shipping sources. Analysis of the combined data yielded the following observations.

At each station, a markedly greater pressure level was seen when the maximum in the cardioid was pointed eastward toward the coast compared to that when the cardioid was aimed seaward. This horizontal anisotropy, expressed in terms of an intensity ratio shoreward versus seaward, reached 10 dB at around 400 Hz, 8.5 km from the beach during heavy surf conditions (see Figure (2)). Interestingly, a slight north-south anisotropy was observed favoring the northerly direction away from Pt. Pinos, the prominent headland at the southwest corner of the bay. The spectral range of the anisotropy corresponds with the spectral range of ambient noise observed due to breaking waves in deep water (Carey and Fitzgerald, 93).

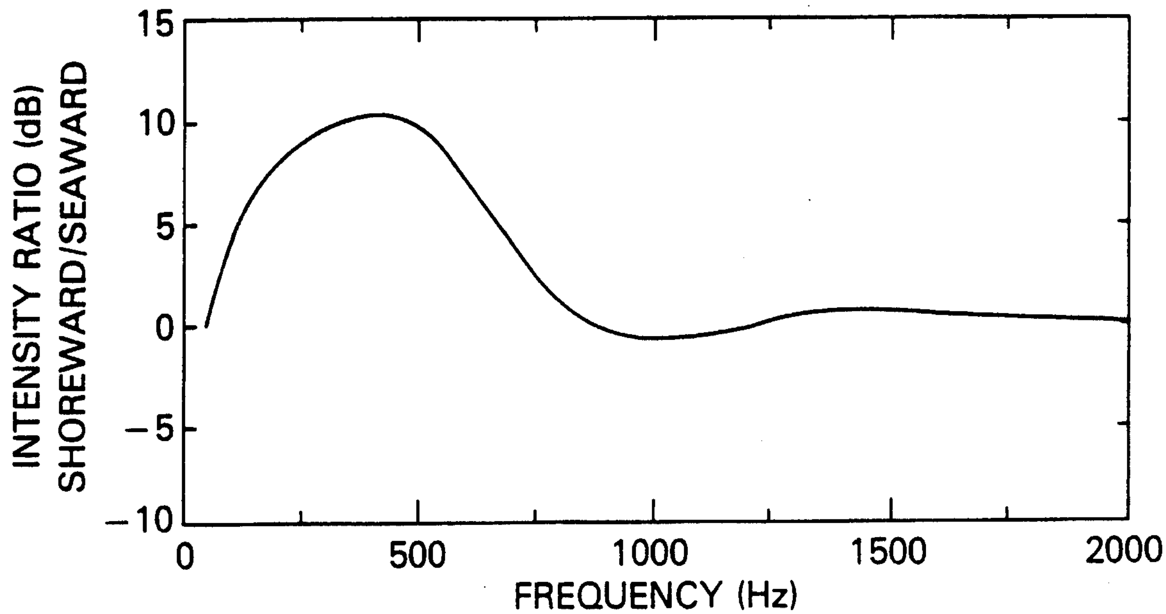

Figure 2. Ratio of intensity spectra of cardioid beam output when oriented shoreward and seaward during heavy surf conditions at Station 7 on 27 March 1981 (from Wilson et al., 85).

Wilson et al. (85) reported that sound pressure level variations with time (surf beat) were detectable within 2 km of the beach. This temporal variation was most notable in the frequencies across which the anisotropy was observed. Figure (3) demonstrates this by contrasting noise spectra measured 200 m from the beach, one taken as a wave was breaking nearby and the other short time later during a period of relative calm.

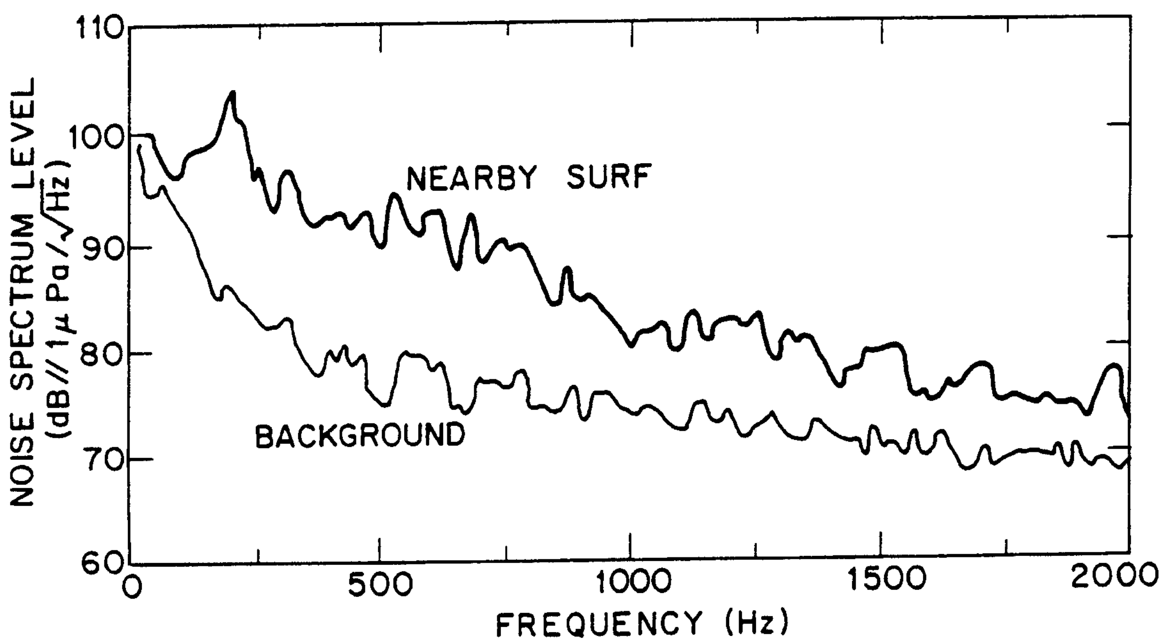

Figure 3. Sound pressure spectrum levels from a bottom-mounted hydrophone 200 m seaward from the surf zone illustrating temporal changes in levels with the breaking of waves. The upper spectrum was made at a time of nearby heavy surf. The lower curve was made a few minutes later during a quiet period (from Wilson et al., 85).

The omnidirectional pressure spectrum level decreased with range from the beach over the same frequencies in which the horizontal anisotropy was observed, that is, roughly 100 Hz to 700 Hz (see Figure (4)). The ultimate conclusion of the experiments was that surf-generated noise does contribute significantly to the overall shallow water ambient noise field in Monterey Bay. Not available during these experiments was a measured or modelled assessment of the TL characteristics of the environment.

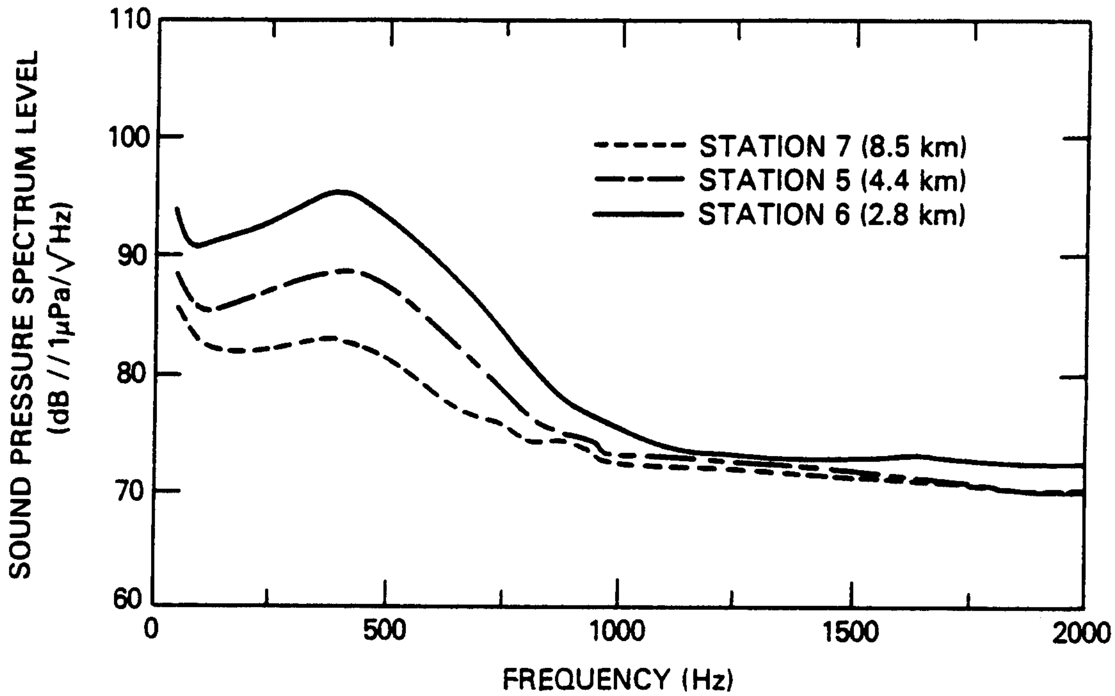

Figure 4. Sound pressure spectrum levels from omnidirectional hydrophone output at ranges 2.8, 4.4 and 8.5 km from shore during heavy surf conditions on 27 March 1981. Corrected for system response (from Wilson et al., 85).

B. DESCRIPTION OF MODELS USED

Analysis of shallow water acoustic energy propagation over the frequency range considered here is best done using a fully coupled normal mode model in which acoustic energy that enters the sea bed and refracts back into the water column is added in proper phase with the acoustic energy propagating in the water column. The use of ray models is precluded due to the frequency range (a few hundred Hertz) and water depth (1-20 m) involved. The number and complexity of bottom interactions of propagating acoustic energy, the variability of the bottom slope, and shoreward shallowness warrant the use of a fully coupled normal mode model. The Finite Element Parabolic Equation (FEPE) model (Collins, 88) was chosen due to its availability, its demonstrated performance in very shallow water (2 m), and its suitability for shallow water acoustic research as reported by McGirr and King (89). The SACLANT Normal Mode Acoustic Propagation (SNAP) model is an uncoupled normal mode model. This model was tested but, as expected, it showed excessively large propagation loss because the transfer of energy between modes is not included in SNAP's TL estimate. FEPE model runs were made for frequencies from 50 Hz to 1000 Hz to estimate the TL of acoustic energy seaward from a 2 m deep surf zone.

A geoacoustic model of the environment, from the ocean sea surface into bedrock, is an essential input for the propagation loss model chosen. Hamilton (80) and Richardson and Briggs (93) provide generic, sufficiently detailed geoacoustic modelling methods and an important subset of data. Detailed bathymetric charts of Monterey Bay were provided by Chase (93). Chin et al. (88) provided sediment thickness information within the bay. The studies of Bieda (70) and Kramer (73), along with a database from the National

Geophysical Data Center, Boulder, Colorado provided qualitative characteristics of bottom sediment in the bay. McCulloch and Greene (90) and Welday and Williams (75) provided qualitative characteristics of the sub-bottom.

III. MODEL CONSTRUCTION AND THEORY

A. INTRODUCTION

Chapter III consists of four sections. The first section describes the geoacoustic model used to determine the TL for Monterey Bay. The second section elaborates on the Hamilton (80), and Richardson and Briggs (93) geoacoustic methodologies. The third section discusses the FEPE TL model used in the analysis. The fourth section presents the method by which modelled TL and the measured noise levels were used to compute the spectral surf zone source level densities.

B. PROPAGATION PATHS

The first step in building a range-dependent geoacoustic model is to specify propagation paths of interest. For the case of Monterey Bay, Wilson et al. (85) provided one such specification.

For purposes of evaluating the potential for the propagation of surf noise, three distinct transmission paths were geoacoustically modelled and are shown in Figure (5). The "Wilson Line" extends westward orthogonally from the Ft. Ord beach. Station 5 from Wilson et al's. 1981 experiment lies roughly 4.4 km seaward (west) of the beach and Station 7 lies roughly 8.5 km seaward. Station D lies 1.2 km shoreward of Station 5 (not shown). A path from Pt. Pinos north to Station 7, 6934 m distant, and a path northeast to Station 5, 7407 m distant, were also modelled. The bottom profile along these three paths is shown in Figure (6).

To assess the reasonableness of the FEPE-derived TL results along these three paths, plots of purely cylindrical ($1/r$) and spherical ($1/r^2$) spreading were included on the graphs. Also for comparison, along Wilson's Line and the path from Pt. Pinos to Station 7, TL model runs were executed with all sediment removed and the basement simulated uniformly to be granite; this represents the ideal fast, low loss hard bottom situation and demonstrates the significant impact on propagation of sea bed interactions within the first kilometer or two from the beach.

In order to more accurately determine the spectral surf noise level density along the Ft. Ord beach, three additional paths were geoacoustically modelled: from Station 7 to points intersecting the coast 2.5 km and 7.5 km north and 5 km south of Ft. Ord. These paths appear as solid lines in Figure (7). The rationale for this selection will become apparent when surf noise density computations are discussed.

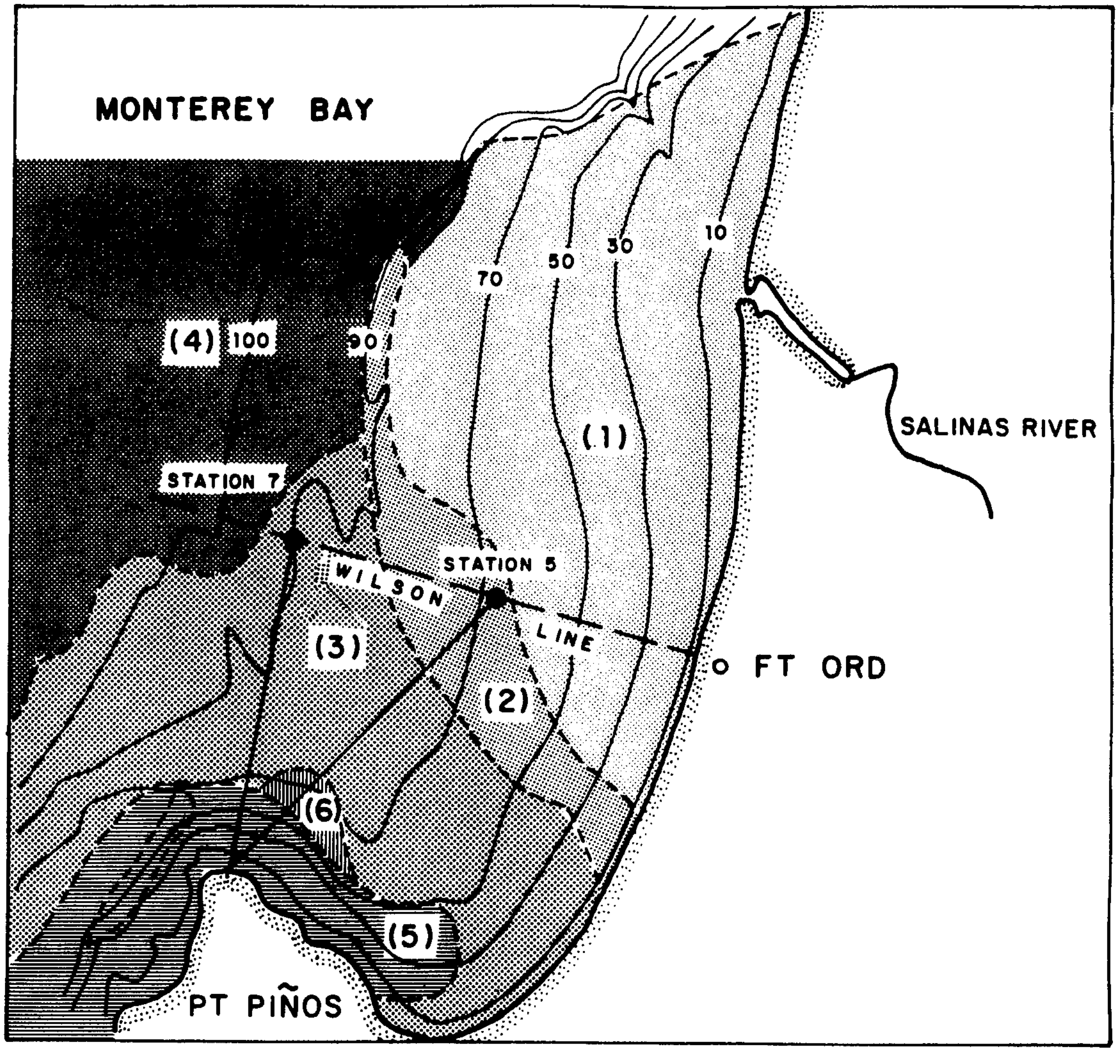

Figure 5. Paths along which propagation loss was modelled for comparison - Monterey Bay. Geoacoustic regions (after McCulloch and Greene (90)): (1) deltaic deposits of Quaternary age overlain by > 3 m unconsolidated deposits of Quaternary age, (2) unconsolidated sand, gravel, clay, and tuff of Pliocene and Pleistocene age (may correlate with the Paso Robles Formation) overlain by > 3 m unconsolidated deposits of Quaternary age, (3) Monterey Formation overlain by > 3 m unconsolidated deposits of Quaternary age, (4) Purisma Formation overlain by > 3 m unconsolidated deposits of Quaternary age, (5) Porphyritic granodiorite, and (6) unconsolidated deposits of Quaternary age.

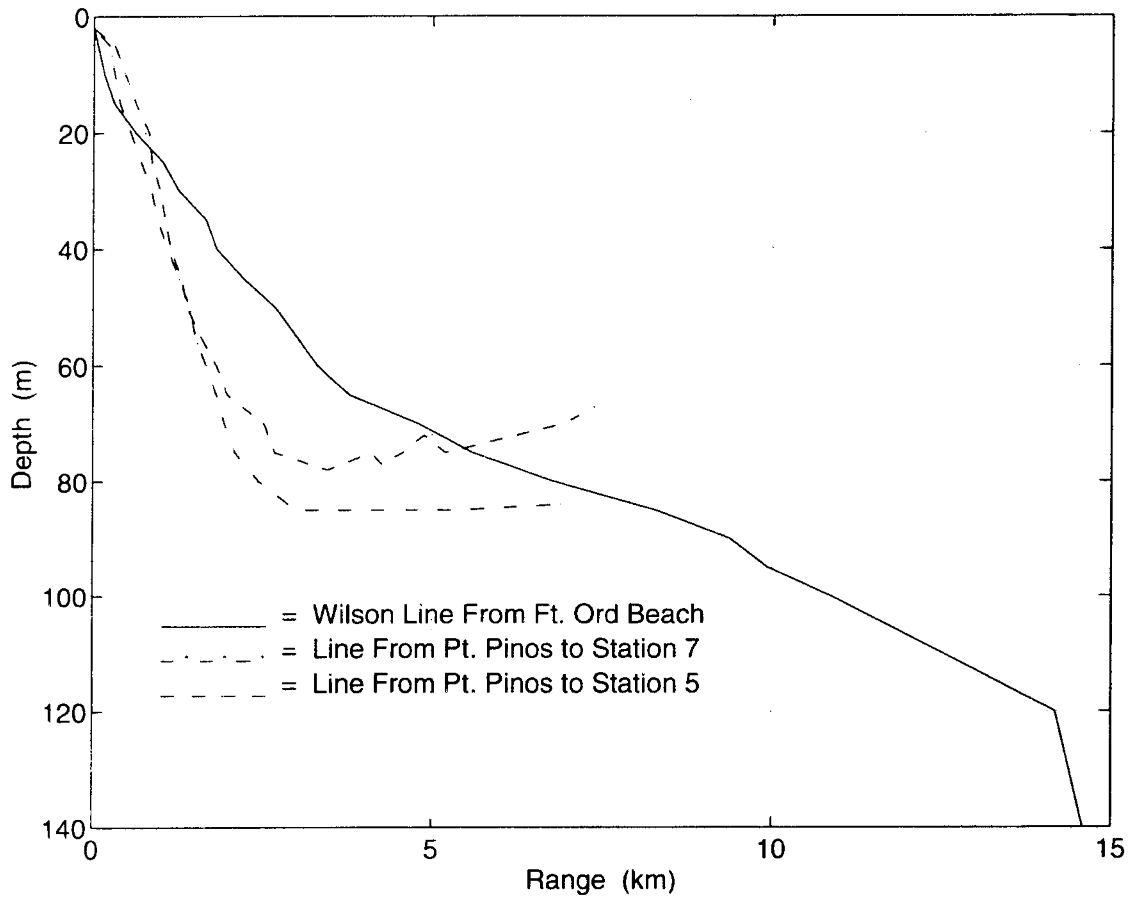

Figure 6. Bottom profiles along three paths in Monterey Bay.

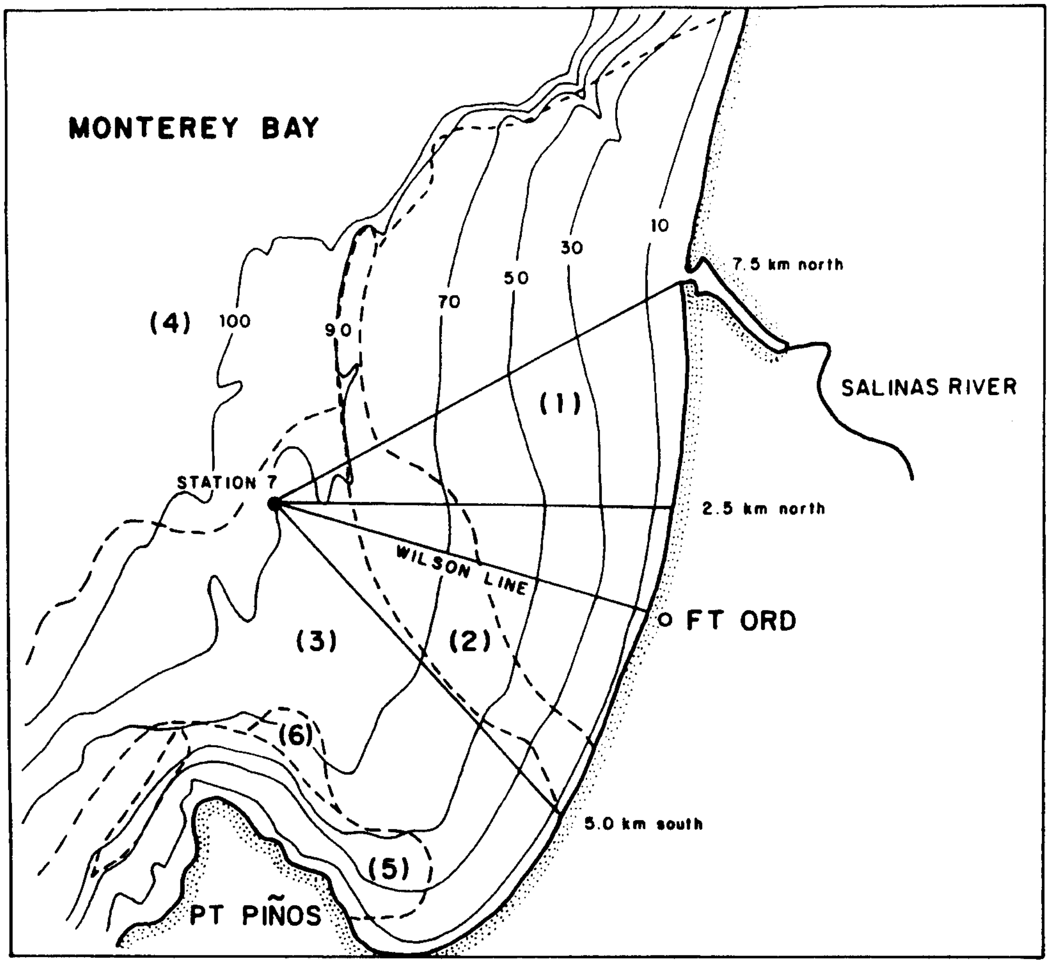

Figure 7. Paths along which propagation loss was modelled for determining spectral surf source level density in Monterey Bay. Figure (5) describes the geoacoustic regions.

C. GEOACOUSTIC MODEL OVERVIEW

Assembling the geoacoustic model, as defined herein, along any one of these paths, amounts to constructing a range-dependent map of the sound speed, the density, and the compressional wave attenuation coefficient from the surface of the ocean through the loose sediment layer beginning on the ocean floor into the harder material layers subtending the sediment. A complete geoacoustic model, ready for processing with the FEPE TL model/program, consists of a sequence in range of vertical geoacoustic profiles each of which defines a column from the ocean surface into the sub-bottom. Profiles are included with sufficient horizontal spacing to ensure that the horizontal resolution of the bathymetry is less than one wavelength.

Each geoacoustic profile consists of four fields, an example of which, for a profile 1025 m from the beach, appears in Table (1). The top field is the water column sound speed profile. The second field is the compressional sound speed profile through the sediment on the ocean floor into bedrock. The third field provides the depth-dependent density in the sub-bottom and the final field provides the depth-dependent compressional wave attenuation coefficient, kp, in decibels per wavelength. The last data entry in this field is an arbitrarily deep highly absorbing layer with a kp of 10.00 dB/wavelength. This high kp serves to make this layer an acoustic sink for wave energy that would normally propagate deeper than the modelled lower limit of the sub-bottom.

Of these fields, the easiest to obtain but the most time variant is the water column sound speed. For Monterey Bay, sound speed versus depth was estimated from expendable bathythermograph data at points obtained at Stations 5-7 in March 1981 (Wilson et al., 85). Extrapolations were made both horizontally toward and away from the beach and vertically to the bottom. Because of the 20 m vertical extent of the water column, isospeed conditions were assumed due to wave mixing. A weak mixed layer of 10 m was evident at Station 6 deepening to about 28 m at Station 7.

1025		range from source (m)
0.00	1500.5	|
4.00	1500.5	|
5.00	1499.0	|
6.00	1497.5	|--- water column sound speed (m/s)
7.00	1496.0	|
9.00	1494.5	|
11.00	1493.5	|
-1.00	-1.00	field divider
11.02	1623.8	|
12.00	1750.2	|
13.00	1810.5	|--- sediment/bedrock
15.00	1850.3	| compressional sound speed (m/s)
16.00	4800.0	|
-1.00	-1.00	field divider
11.02	1.23	|
12.00	1.47	|
13.00	1.76	|--- sediment/bedrock density (g/cm^3)
15.00	1.83	|
16.00	2.75	|
-1.00	-1.00	field divider
11.02	0.37	|
12.00	0.11	|
13.00	0.03	|--- sediment/bedrock compressional
15.00	0.03	| attenuation (dB/wavelength)
16.00	0.10	|
275.00	10.00	|--- absorbing layer
-1.00	-1.00	field divider

Table 1. A sample geoacoustic profile 1025 m from source (beach) modelling an 11 m water column subtended by a 5 m sediment/bedrock structure.

More difficult to determine were the compressional sound speed, density, and compressional attenuation beneath the ocean floor. Hamilton (80) and Richardson and Briggs (93) provide a methodology for accomplishing this with or without bottom and core sample data. Fortunately, for both Monterey Bay and San Diego, such geoacoustic data were available to refine the sediment and sub-bottom sound speed profile.

Chin et al. (88) studied the sedimentary lobe at the mouth of the Salinas River, which enters Monterey Bay 7.5 km north of Ft. Ord. They used high resolution bathymetry to assess, among other things, the sediment thickness across the lobe. The southernmost of their profiling runs (see Figure (8)) lay along the Wilson Line and revealed roughly 2 m of sediment. From that path southward, the 2 m sediment "veneer" dwindles to the vanishing point over the porphyritic granodiorite (granite) basement along the southernmost margin of the bay.

Bieda (70) and Kramer (73) reported detailed results of several grab samples taken over the southern half of Monterey Bay. Qualitative descriptions of historical bottom samples from the bay were also obtained from a marine sediment data base at the National Geophysical Data Center, Boulder, Colorado, from the California Continental Margin Geological Map Series produced by McCulloch and Greene (90), and from the Offshore Surficial Geology of California chart produced by Welday and Williams (75). These were interpreted together, along with the results of Bieda and Kramer, by applying the approaches used by Hamilton (80) and Richardson and Briggs (93) to arrive at the sediment and bedrock sound speed, density, and attenuation coefficient profiles. Profiles were generated for six different sediment regions overlapping four different bedrock formations (see Figure (5)) along the Wilson Line. A fifth bedrock formation, porphyritic granodiorite (granite), was also included in the model along the two paths

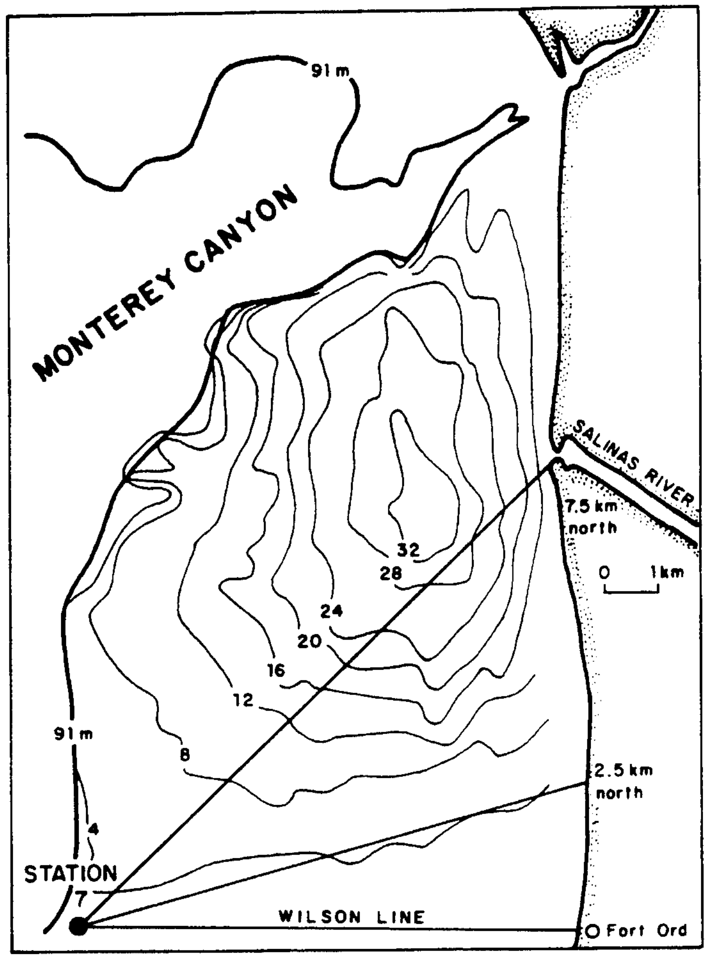

Figure 8. Sediment thickness contours in meters at the mouth of the Salinas River (from Chin et al. (88)) and three paths along which propagation loss was modelled.

extending north from Pt. Pinos. These sediment and bedrock data were then assembled in a data file for use in running the FEPE TL model.

D. GEOACOUSTIC METHODOLOGIES

Hamilton's modelling methodology recognizes eight properties of sediment and rock layers of which three are needed, along with water column sound speed, for input to the FEPE program (the FEPE.IN file). These properties are the sediment and bedrock compressional sound speed, density and compressional wave attenuation coefficient (expressed in decibels per wavelength), all as a function of depth. Implicit is a knowledge of the sediment thickness as well as the nature of the sedimentary material overlying the bedrock.

While Hamilton's work is useful to obtain estimates in the absence of measured data, his technique also serves to emphasize the improved accuracy achieved when measured data are used. Bieda (70) and Kramer (73) measured various sediment properties in Monterey Bay from grab and core samples at several locations many of which coincided well with Wilson's acoustic propagation paths from the Ft. Ord beach. Properties measured that were useful for building the geoacoustic model included sediment density and porosity and the ratio of sound speed in the sediment to sound speed at the bottom of the water column. The sediment sound speed profile can then be estimated using the equation and coefficients in Table IV of Hamilton (80).

For shallow depth sediments (less than 34 m thick in the Salinas River delta and 2 m thick or less from Wilson's Line south to Pt. Pinos) the sediment density may be assumed to be a constant, in light of Figure (22) of Hamilton (80). The sediment compressional wave attenuation coefficient, kp (dB/m-kHz), may be inferred from the sediment porosity using Figure (18) of Hamilton (80) which maps kp as a function of porosity.

The attenuation coefficient, kp, is defined in

$$\alpha_P = kp * f_{kHz}, \tag{1}$$

where α_P is the attenuation coefficient expressed in dB/m, and f_{kHz} is the frequency in kiloHertz. Using Figure (20) of (Hamilton, 80), which shows kp as a function of depth in the sea floor, kp is essentially constant in the first 35 m.

The above process was used to model the bottom seaward of the nearshore sandy regions of Monterey Bay. Coarse sand extends from the surf zone roughly 1000 m to sea and fine sand extends an additional 2000 m beyond that along the relatively steep 1°-2° slope from shore (Welday and Williams, 75). For these two regions, no detailed measurements of sediment properties were available. The density, porosity and sound speed ratios are given for coarse and fine sand in Table I, Hamilton (80), the attenuation coefficient is derived from Hamilton (80), Figure (18), and the sound speed as a function of depth is computed using

$$V = K * D^{0.015}, \tag{2}$$

where V (m/s) is the compressional wave speed, D (m) is the depth in sand and K is a constant obtained by applying D = 0.05 m and V_o = sound speed ratio times the sound speed at the bottom of the water column (Hamilton, 80).

Some of the measured data of Bieda (70) and Kramer (73) were inconsistent or appeared to be in error, requiring estimation of sediment properties as in the following examples. One sample (Bieda, 70) yielded a sound speed ratio of 0.999 whereas all others yielded ratios above 1.00. Measured density and porosity were observed to be consistent based on computation of mineral grain density (which should be 2.5-2.8 g/cm^3) (personal communication with Bachman). Measured porosity was then used with a formula contained in Table (3) of Richardson and Briggs (93) to compute a more appropriate sound speed ratio from which sediment sound speed as a function of depth was determined as described above. A second sample (Kramer, 73) yielded a compressional wave speed of 1367 m/s, clearly in error, and no value for porosity. However, mean grain size was measured as

$$\phi=-\log_2(d)=1.40, \tag{3}$$

where d is mean grain diameter (mm). From this value, using formulas in Table (3) of Richardson and Briggs (93), one can infer sediment compressional sound speed, density, porosity, and thence kp, the attenuation coefficient.

It should be noted that the attenuation coefficient given by the references cited is in units of decibels per meter per kiloHertz (dB/m-kHz). The FEPE program requires that the attenuation be specified in decibels per wavelength which may be computed by multiplying the coefficient in dB/m-kHz by the average sediment compressional sound speed in kilometers per second.

The geoacoustic properties of the various types of bedrock identified by McCulloch and Greene (90) were taken from various references. Compressional sound speed was taken from Ridlon (70), density was taken from Figure (1) of Hamilton (78), and compressional attenuation was taken from Figure (3) of Hamilton (59). In the case of the porphyritic granodiorite floor along the south bay coast, properties for basalt were taken from Northrop (78). (Personal communication with Ryan and Bachman)

A small segment of quaternary deposits comprised the entire ocean floor column beyond the granite region northeast of Pt. Pinos. For this area, which lies in a sandy region according to Welday and Williams (75), properties were taken or derived using Hamilton (80).

E. FEPE MODEL

The Finite Element Parabolic Equation TL model solves, for the range-dependent ocean environment, higher-order parabolic equations to compute complex acoustic pressures. It employs Galerkin's method to develop a numerical solution which is then operated on using the Crank Nicolson integration method. Model accuracy is comparable to that of the coupled mode solution. (Collins, 88)

Phase errors which arise in cases of high-angle propagation and increase with range when using the narrow angle parabolic equation are significantly reduced with the discovery by Collins of a family of higher-order parabolic equations. This model runs efficiently on a workstation, and is reported to be accurate for long-range and high angle (close to 90 degrees) propagation. (Collins, 88)

A single receiver depth is normally programmed when running FEPE, and the model calculates TL at all ranges assuming that the receiver is at this depth. Thus, for short ranges from the beach at which the bottom is shallower than the programmed receiver depth, FEPE computes TL for a receiver buried in sediment or bedrock. All curves in this paper are based on a receiver depth of 30 m, and the range offshore at which water depth reaches 30 m is annotated on the curves. The drop in TL at this point is distinctive on all curves above 50 Hz. This anomaly is of no consequence in this paper.

The FEPE model assumes a seawater density of 1 g/cm^3 and negligible seawater attenuation. It also assumes that the ocean surface and bottom are smooth thus neglecting scattering effects. Scattering effects may be approximated by simulating water column properties at the surface and floor of the ocean, but this was not attempted. For the propagation ranges and frequencies below 1 kHz discussed in this paper, these limitations pose no serious problem. For frequencies greater than 1 kHz, the TL results are unrealistically low due to the smooth boundary assumption. The FEPE model also does not linearly interpolate sound speed, density, or attenuation coefficients in range. A sufficiently dense set of profiles is thus needed to smooth parameter values appropriately to avoid anomalies caused by unrealistic step changes in those values.

F. SPECTRAL SOURCE LEVEL DENSITY OF THE SURF

In the absence of shipping, bioacoustic noise, rain, and other intermittent sources of noise, the two most common contributions to the noise spectrum level sensed by an omnidirectional hydrophone in shallow water are the noise associated with wind and wave agitation of the sea surface and those associated with breaking surf. The former contribution, which will be referred to as sea state noise, is uniformly generated close to and above the hydrophone. Such noise levels are a function of wind speed or wave height and have been extensively studied and documented by Knudsen et al. (48), Wenz (62), Wilson (83), and others. The surf-generated spectrum level, by comparison, can be generated non-uniformly along a diverse coastline geography, can suffer path-dependent propagation loss, and, in contrast to local sea state noise, arrives along near-horizontal paths. It is also affected by sea state.

Because few, if any, measurements of the source level spectrum due to breaking surf exist, it is necessary to derive such a source level spectrum. An empirical approach in this paper is desirable given the high quality off-shore ambient noise measurements available and the lack of accepted theories for deriving spectral surf source level. The following describes the development of a model to accomplish this based on several simplifying assumptions. Figure (9) and the following equation for the acoustic intensity received at an omnidirectional hydrophone near a coastline, from only the two contributions given above, serve as bases for discussion.

$$I_{RECEIVER}=I_{SEASTATE}+SI*\int\frac{dx}{IL}, \tag{4}$$

where SI, the spectral surf source intensity per meter of beach, is assumed to be dependent on frequency, sea state, and beach type. It is assumed to be uniform along the full beach length. The differential distance along the beach on which surf is breaking is represented by dx. Transmission loss, the loss of acoustic energy as it propagates seaward to a receiver, is a function of both frequency and distance along the beach. In Equation (4), IL, the intensity loss, is just linearized TL,

$$IL=10^{\frac{TL}{10}}.$$

The path of noise energy from each surf zone increment to the hydrophone will be unique depending primarily on the sediment vertical and horizontal distribution and the bedrock distribution beneath the sediment. Since the two contributions to the received intensity at the hydrophone are assumed to be incoherent sources, the acoustic intensities are summed.

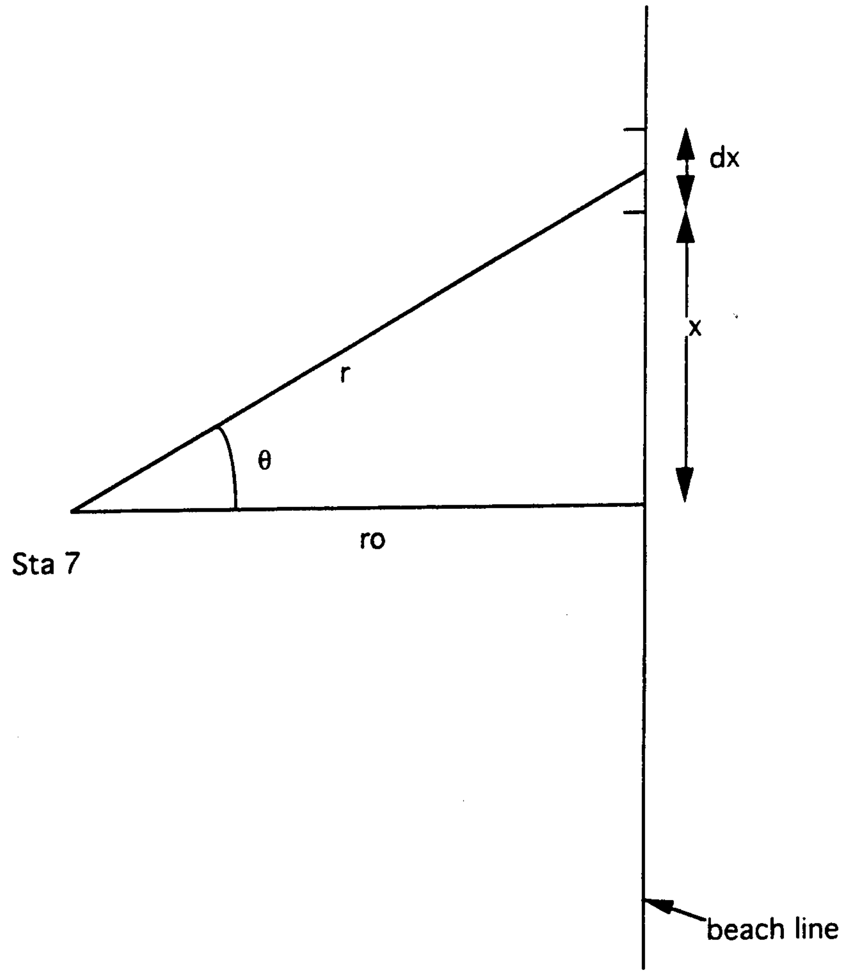

Figure 9. Simple linear geometry for computing spectral noise level density of the surf.

The spectral surf source intensity can be found by manipulating Equation (4) as shown:

$$SI = [I_{RECEIVER} - I_{SEASTATE}] / \int \frac{dx}{IL}, \tag{5}$$

which can be expressed as a summation,

$$SI = [I_{RECEIVER} - I_{SEASTATE}] / \Sigma_i \frac{\Delta x_i}{IL(f, x_i)}. \tag{6}$$

Here, dx of Equation (5) is replaced by Δx_i, and $IL(f,x_i)$ is dependent on both frequency and the point on the beach from which it is modelled. Spectral source level density can then be calculated as

$$SL_{SURF}=10\log(SI)-10\log(I_{REF})=10\log(SI)+182, \qquad (7)$$

where SL_{SURF} is expressed in dB ref. 1 $\mu Pa/\sqrt{Hz}/m$ and I_{REF}, the intensity produced by a plane wave with an rms acoustic pressure of 1 μPa, is given by

$$I_{REF}=\frac{P_{RMS}^2}{\rho c}=6.67*10^{-19}W/m^2. \qquad (8)$$

For calculations of spectral surf source level density in Monterey Bay, two surf conditions were evaluated at different stations on different days. Heavy surf source level density was evaluated from the omnidirectional acoustic measurements at Station 7 on 27 March 1981. Light surf source level density was evaluated from the measurements at Station D, 3.2 km off the Ft. Ord beach, on 16 April 1981. The omnidirectional hydrophone received noise intensity at 50, 300, 500, and 1000 Hz was calculated from average one-third octave band levels in Table V of Elles (82) which are absolute levels, corrected for system response, of the data in Wilson et al. (85).

Sea state spectral intensities at the same frequencies were taken from open ocean, primarily wind-generated, noise spectrum levels given in Wilson (83). The Wilson (83) levels were used because they are a measure of the noise caused mainly by sea surface agitation induced by wind and wave action. They do not include effects of shipping. Average wind speeds of 35 kts and 10 kts, the respective wind conditions during the 27 March and 16 April 1981 measurements, were applied to Figure (1) of Wilson (83) for Stations 7 and D, respectively.

TL was modelled along four distinct paths from the beach to Station 7 at the four frequencies of interest using the FEPE program. These data were also extrapolated to determine the TL to Station D for the measurements made three weeks later. The water column sound speed profile was less negative on 16 April than it was on 27 March, an effect that introduced minor errors into these TL values.

It should be noted that modelling TL with the FEPE program at other than orthogonal paths to the beach introduces uncertainties. The tilt of the bottom, as seen from the hydrophone location along the propagation path, grows as the sine of the angle between that path and the orthogonal path until it reaches the bottom slope away from the beach. Along the Wilson Line, this slope is around 0.75° at Station D. This tilt complicates the TL as reported in Paliatsos (89).

An assumption was made that the surf noise contribution from distant beaches, e.g., from Santa Cruz to the Salinas River, was negligible due to their great distance from Station 7. The surf noise contribution from the coast 5 km south of Ft. Ord west to Pt. Pinos was also assumed negligible since the westerly direction of the surf would be expected to generate little wave energy in the surf zone along that north-northeast-facing coastline. The effective source line was thus assumed to be about 12.5 km long from 5 km south of Ft. Ord to 7.5 km north of Ft. Ord.

Because it was not feasible to evaluate the TL as a continuous function of position along the beach to Station 7, the following approach was taken. The IL under the summation of Equation (6) was averaged for each of the three segments of beach shown in Figure (7) as

$$IL(f,x_i)_{AVERAGE}=\frac{10^{\frac{TL_{NORTH}}{10}}+10^{\frac{TL_{SOUTH}}{10}}}{2}. \tag{9}$$

The Δx_i of Equation (6) was the distance between those points. The TL curves of Figure (10), (13), (14), and (15), respectively, were used to evaluate TL from Ft. Ord, a point 5 km south of Ft. Ord, and points 2.5 km and 7.5 km north of Ft. Ord out to Station 7.

Simple numerical integration was used in a MATLAB^R program to derive surf zone spectral source intensity per meter of beach based on Equation (6) in which $IL(f,x_i)$ represents the relation in Equation (9). The spectral intensities per meter of beach were then converted into source level densities and graphed. The results appear in Figure (18).

For light surf source level density calculations at Station D, the same approach was taken. The TL curves of Figure (10) were used to evaluate TL from both Ft. Ord and the point 2.5 km north of Ft. Ord out to Station D. Figure (13) and Figure (15) were used to estimate TL to Station D from points 5 km south and 7.5 km north of Ft. Ord respectively. Equation (6) was used again in a MATLAB^R program to derive low surf noise spectral source intensity. The graphed results of these spectral source level densities appear in Figure (19).

IV. RESULTS AND DISCUSSION

A. TRANSMISSION LOSS MODELLING RESULTS

Figures (10) through (12) show Monterey Bay TL results for the Wilson Line and paths from Pt. Pinos to Stations 5 and 7 respectively. Figures (13) through (15) show TL results for paths from Station 7 to three other points along the Ft. Ord coastline as indicated. Each figure is comprised of a set of four curves, one for each frequency of interest. For Monterey Bay, which was modelled with 1 m bathymetric resolution, these frequencies are 50, 300, 500, and 1000 Hz.

All plots were derived from running the FEPE TL program with a unique geoacoustic model input comprised of limited measured data and considerable estimated data based on qualitative assessments of sediment and sub-bottom character and extrapolated sediment thickness. The geoacoustic model input to FEPE was a sequential set of profiles defining the sound speed, density, and attenuation characteristics of the waveguide from the ocean surface into the sea bed. Each FEPE run used the Green's Function starter option within the FEPE program due to the very shallow modelled depth of the source, i.e., 1 m deep in 2 m of water. The modelled receiver depth was 30 m, approximately the depth of the sonobuoy hydrophones employed by Wilson et al. (85). The data were smoothed by a program that linearly averaged twenty data points at 600 evenly spaced intervals in the TL data set. This filtering process produced a TL result that contours the lower envelope of the raw data.

Each plot displays a cylindrical ($1/r$) and a spherical ($1/r^2$) TL curve for comparison with the modelled data. Each plot displays the basement geoacoustic regions, after McCulloch and Greene (90), a legend for which appears in Table

(2). Figure (5) gives a geographical representation of these regions in Monterey Bay. The plots depict the sediment distribution from the beach seaward as described in the caption. Also shown along the abscissa of the charts is the range of the 30 m contour, at which point the modelled receiver depth becomes equal to the water depth (see Section III.F.), and station (hydrophone) location where appropriate.

Abbrev.	Region	Description
Q/Qd	1	deltaic deposits of Quaternary age overlain by > 3 m unconsolidated deposits of Quaternary age
Q/QTpr	2	unconsolidated sand, gravel, clay, and tuff of Pliocene and Pleistocene age (may correlate with the Paso Robles Formation) overlain by > 3 m unconsolidated deposits of Quaternary age
Q/Tmm	3	Monterey Formation overlain by > 3 m unconsolidated deposits of Quaternary age
Q/Tpp	4	Purisma Formation overlain by > 3 m unconsolidated deposits of Quaternary age
gdp	5	Porphyritic granodiorite
Q	6	unconsolidated deposits of Quaternary age

Table 2. Legend of geoacoustic regions - Monterey Bay - (from McCulloch and Greene (90)). (Region numbers correspond to Figure (5))

From a macroscopic view, TL results show that paths with a variety of different geoacoustic properties permit seaward propagation of surf-generated noise. A comparison of the sediment thickness and character, the sub-bottom character, and the bottom slope between the Wilson Line and northward paths from Pt. Pinos clearly shows the marked differences of the geoacoustic models for these paths. In spite of these differences, Figures (11) and (12) (propagation loss from Pt. Pinos) reveal that, for frequencies above 300 Hz, acoustic energy propagating along these paths suffers only 70-80 dB TL at 7 km. Figure (10) (propagation loss along Wilson's Line) reveals that acoustic energy propagating along this path suffers only 80-90 dB TL at 15 km. The energy at 50 Hz does not propagate due to wave guide cutoff effects.

Looking more closely, it is apparent that the range dependent fluctuation of even filtered TL can vary from a few to 30 dB. The standard deviation of the TL (decibel space) results beyond about 5 km ranges from 4 to 7 dB. Nonetheless, the TL results show some dependence on the specific nature of the geoacoustic environment and on frequency. Comparison of Figures (10) and (12) at 300 Hz show that there is about 5 dB less TL from the beach to 5 km along Wilson's Line than along a path from Pt. Pinos seaward 5 km. Surprisingly, at 500 Hz, the TL 5 km along Wilson's Line exceeds the TL 5 km from Pt. Pinos by about 5 dB.

TL results described below also show that sea bed features within a few kilometers of the beach have a greater affect on TL than more distant features. Figure (16) shows TL results for a hybrid environment in which the ocean floor from Pt. Pinos to Station 7 is uniformly modelled as granite with no overlying sediment, the best possible transmission condition. Figure (12) shows TL results for the normal sediment overburden model from Pt. Pinos to Station 7; the sea bed off Pt. Pinos is granite out to about 2 km with no overlying sediment. From 2 to 4 km, 1 m of sediment is modelled and from 4 km to Station 7, 2 m of sediment is modelled. A comparison of these figures reveals little difference in TL versus range. A comparison of two similar TL curves along Wilson's Line shows that, for all frequencies, TL is 10-15 dB higher with a normal sediment overburden (2m thick along the entire path and in particular along the first 2-3 km) compared with a hard, reflective bottom. Figure (17) shows TL results for an artificial granite sea bed with no sediment. Figure (10) shows TL results along this path for the natural sediment overburden condition. It may be concluded that TL occurring in the first two kilometers of propagation away from the beach determines the basic character of the overall TL curve.

B. SPECTRAL SOURCE LEVEL DENSITY CALCULATIONS

The results of using Equations (6) and (9), the estimated values of TL illustrated in Figures (11)-(17), and the estimated noise spectrum levels due to wind and wave noise (sea state noise) from Wilson (83) to calculate the acoustic noise spectral source level density at the surf zone are presented in Figures (18) and (19). The source level densities for heavy surf at Ft. Ord beach were estimated to be 129 dB, 118 dB, 114 dB, and 102 dB for 50 Hz, 300 Hz, 500 Hz, and 1000 Hz respectively. The source level densities for light surf were estimated to be 116 dB, 91 dB, 93 dB, and 86 dB for the same respective frequencies. In Figure (19), one quickly notices the deviation from a smooth decreasing exponential curve at 300 Hz for the low surf condition. This is driven by the low modelled transmission loss along Wilson's Line (57 dB). Given the decreasing exponential form of both the high surf source level density results and the spectral noise levels measured 200 m from the beach (Figure (3)), one might have expected the low surf source level density results to be a smooth decreasing exponential also. Modelling TL with a fully coupled normal mode model might yield a higher TL at 300 Hz thus raising the calculated source level density.

Uncertainty values are available for the measured noise and the sea state contribution to that noise, but meaningful estimates of the uncertainty of the source level density calculations are impossible to make. The standard deviation of the modelled transmission loss was determined but this is not a good measure of the uncertainty in the geoacoustic and FEPE models. Extreme values of source level density, given the values described above, range from +10 dB to -21 dB. The input parameters and output source level densities for the four frequencies of interest are summarized in Tables (3) and (4) for high and low surf conditions at Stations 7 and D respectively.

A way of evaluating the source level density results is to calculate pressure spectrum levels that would be expected at Station 7 and Station D if the only contribution to the measured ambient noise were from the surf zone, using the following equation,

$$PSL = ISL = 10\log\left(\frac{I_{MEASURED} - I_{SEASTATE}}{I_{REF}}\right). \tag{10}$$

PSL and ISL are equal since reference intensity and reference pressure units are compatible. PSL results are given in Tables (3) and (4) and may be compared to levels due to other well known sources. The estimated 300 Hz ambient noise pressure spectrum level at Station 7 due solely to surf breaking on the Ft. Ord beach is 81 dB. At 300 Hz, the pressure spectrum level contribution of heavy shipping to deep-water ambient noise is 70 dB (Ross, 76), and the pressure spectrum level contribution of 50 kt winds is 76 dB (Wilson, 83). The estimated 500 Hz ambient noise pressure spectrum level at Station 7 due to surf breaking on the Ft. Ord beach is 78 dB. At 500 Hz, the pressure spectrum level of 50 kt winds is 74 dB.

	50 Hz	300 Hz	500 Hz	1000 Hz
Observed Noise Level*	82 ± 2	82 ± 2	79 ± 2	72 ± 2
Estimated Wind and Wave Noise Level*	75 ± 5	74 ± 5	73 ± 5	71 ± 5
Surf Noise Source Level Density**	129	118	114	106
Estimated PSL due to Surf Noise Alone*	81	81	78	65
Fraction of Total Intensity from Surf Noise***	84	86	75	65

Table 3. Input and output values for heavy surf source level density calculations at Station 7. The standard deviation of TL used to obtain Intensity Loss ranged between 4 and 7 dB.
* dB ref. 1 $\mu Pa/\sqrt{Hz}$.
** dB ref. 1 $\mu Pa/\sqrt{Hz}/m$ at 1 m.
*** percent.

	50 Hz	300 Hz	500 Hz	1000 Hz
Observed Noise Level*	74 ± 2	70 ± 2	68 ± 2	60 ± 2
Estimated Wind and Wave Noise Intensity Level*	55 ± 5	58 ± 5	57 ± 5	55 ± 5
Surf Noise Source Level Density**	116	91	93	86
Estimated PSL due to Surf Noise Alone*	74	70	68	58
Fraction of Total Intensity from Surf Noise***	99	94	92	68

Table 4. Input and output values for light surf source level density calculations at Station D. The standard deviation of TL used to obtain Intensity Loss ranged between 4 and 7 dB.
* dB ref. 1 $\mu Pa/\sqrt{Hz}$.
** dB ref. 1 $\mu Pa/\sqrt{Hz}/m$ at 1 m.
*** percent.

Still another way to compare the effect of the surf generated noise is to calculate what fraction of the intensity at Stations 7 and D is due to the surf generated noise.

$$PERCENTAGE=100*\left(\frac{I_{MSEASURED}-I_{SEASTATE}}{I_{MEASURED}}\right). \quad \textbf{(11)}$$

These results are given in Tables (3) and (4). Surf noise is estimated to account for a high percentage (75%-94%) of the measured ambient noise intensity at 300 and 500 Hz for both surf conditions as shown in Tables (3) and (4).

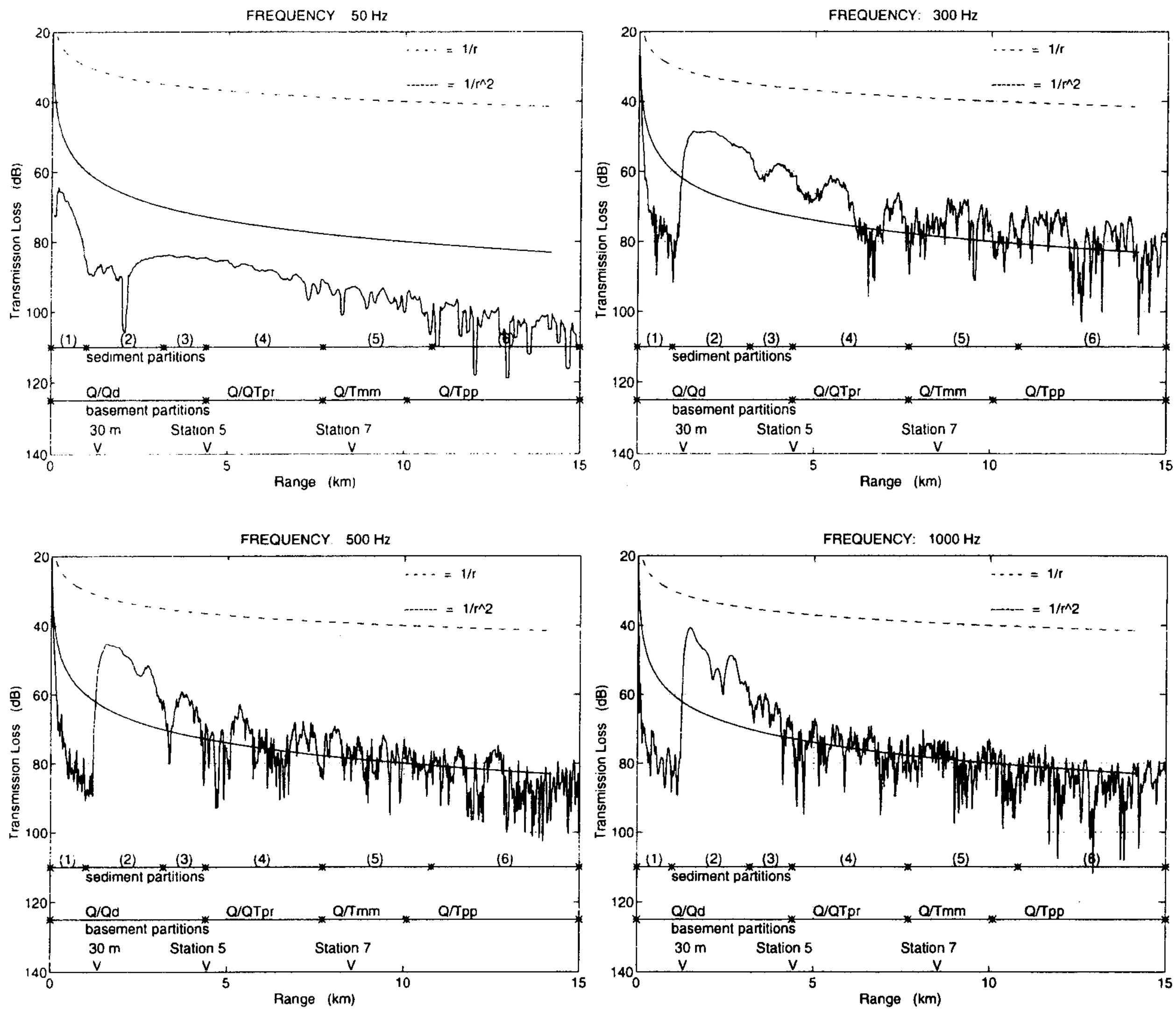

Figure 10. Transmission loss along Wilson's Line for 50, 300, 500, and 1000 Hz. Sediment types: (1) coarse sand, (2) fine sand, (3) silt, (4) clayey silt, (5) sand-silt-clay, (6) sand, muddy. The distance to Stations 5 and 7 are noted as is the range at which the water depth deepens to 30 m, the modelled receiver depth. Cylindrical (1/r) and spherical ($1/r^2$) spreading TL curves are shown for comparison.

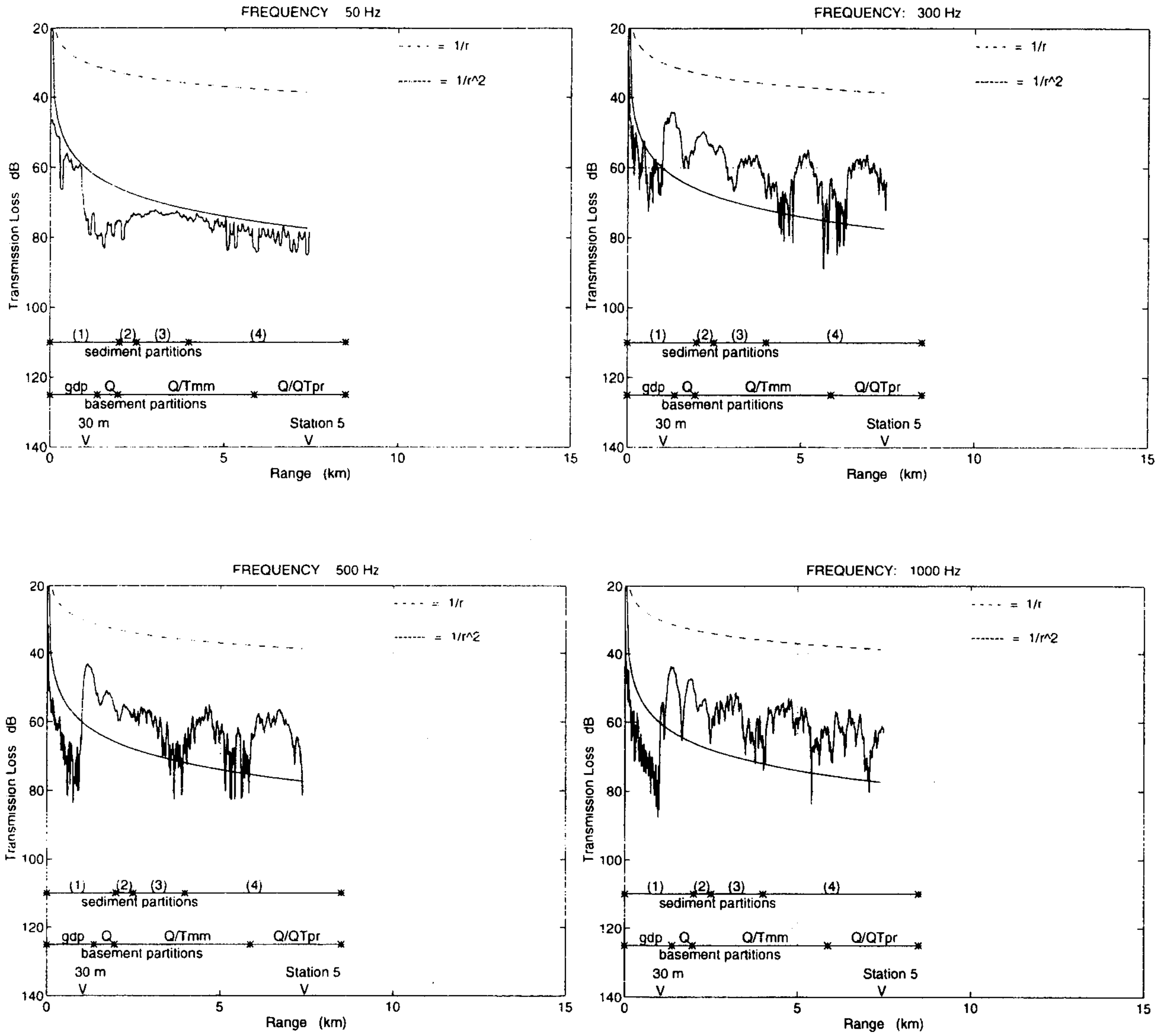

Figure 11. Transmission loss along the path from Pt Pinos to Station 5 for 50, 300, 500, and 1000 Hz. Sediment types: (1) no sediment, (2) 1 m coarse sand, (3) 1 m clayey silt, (4) 2 m clayey silt. (Receiver depth 30 m.)

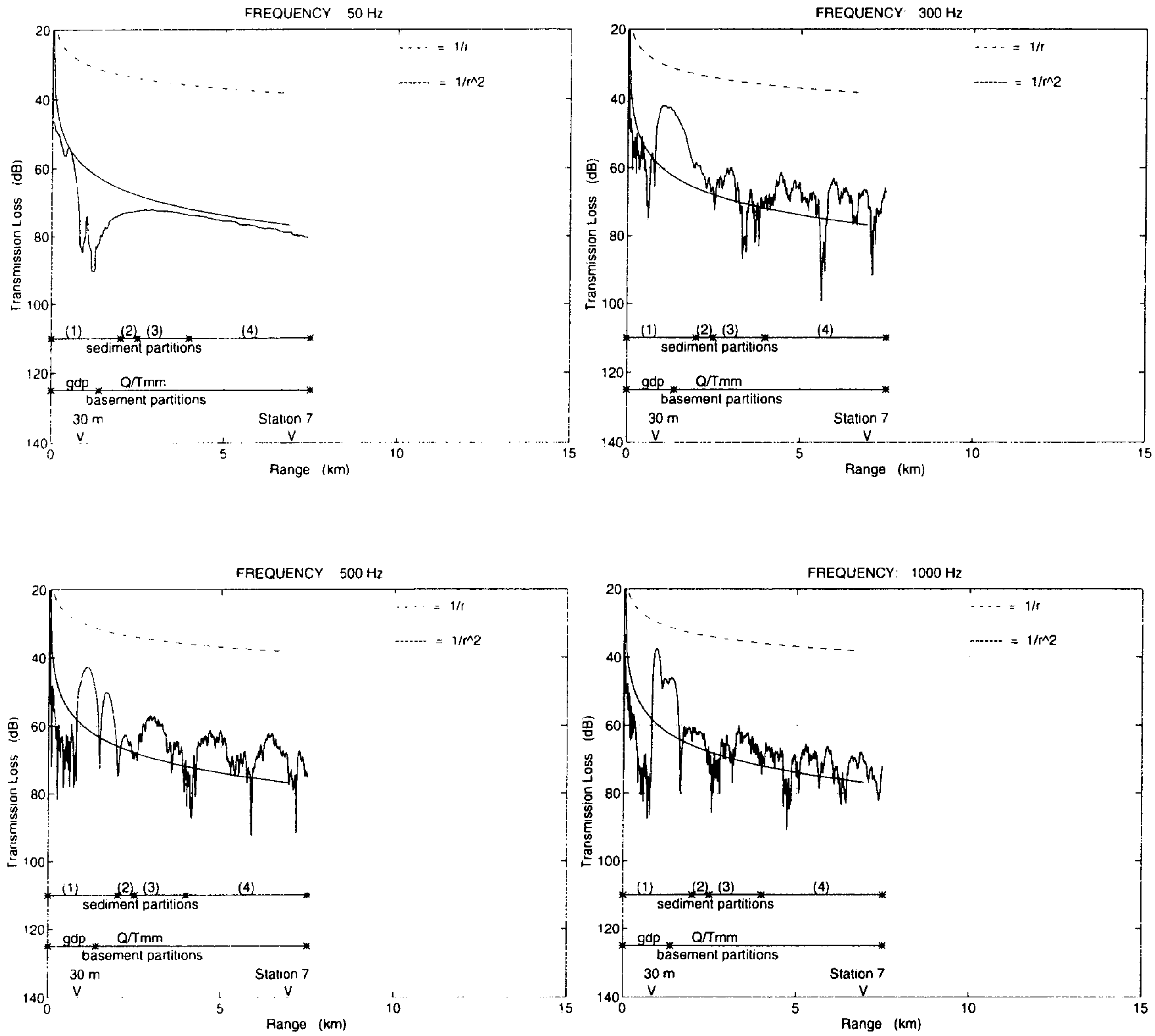

Figure 12. Transmission loss along the path from Pt Pinos to Station 7 for 50, 300, 500, and 1000 Hz. Sediment types: (1) no sediment, (2) 1 m coarse sand, (3) 1 m clayey silt, (4) 2 m clayey silt. (Receiver depth 30 m.)

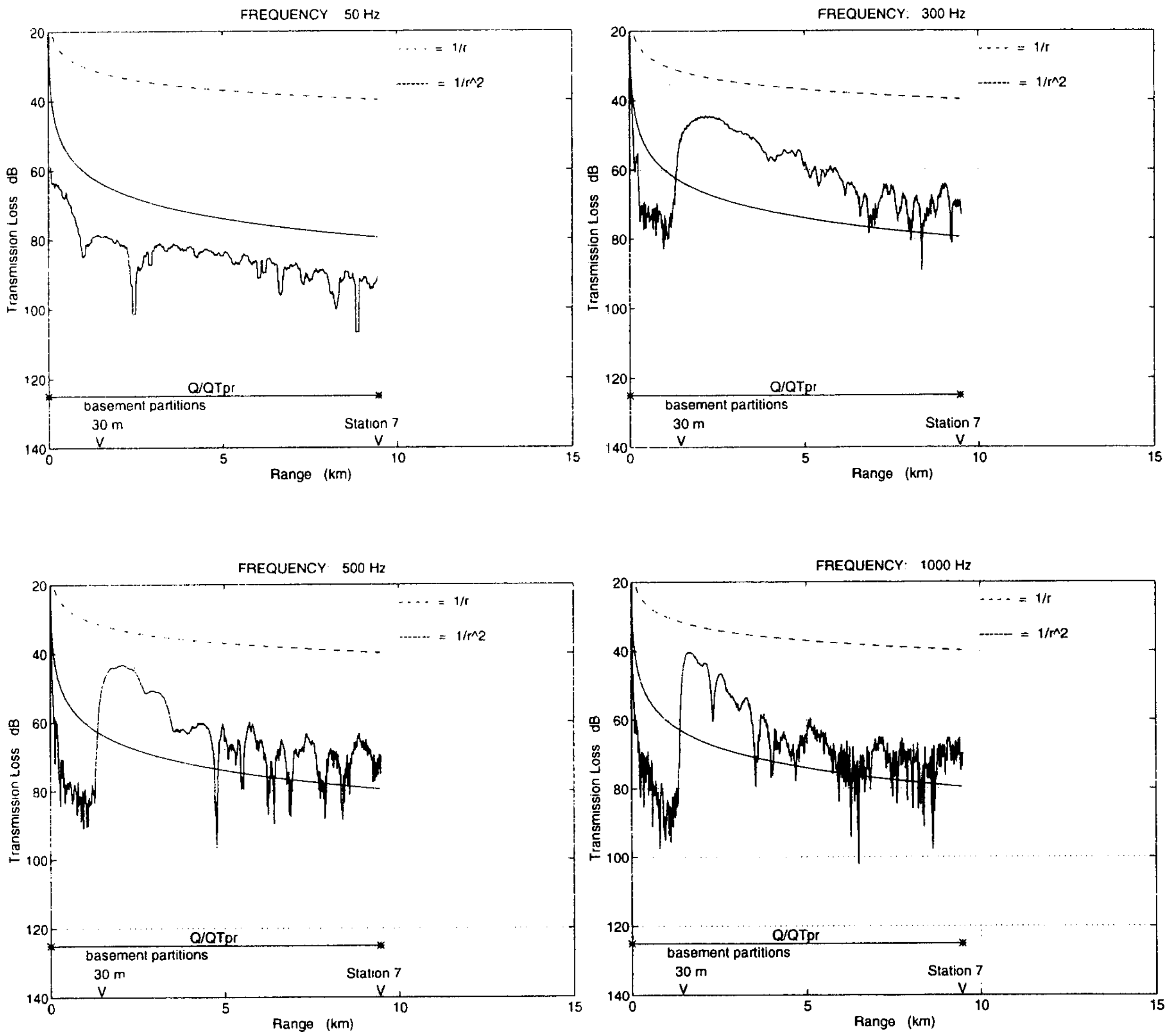

Figure 13. Transmission loss along a path from the beach 5 km south of Ft. Ord to Station 7 for 50, 300, 500, and 1000 Hz. No sediment. (Receiver depth 30 m.)

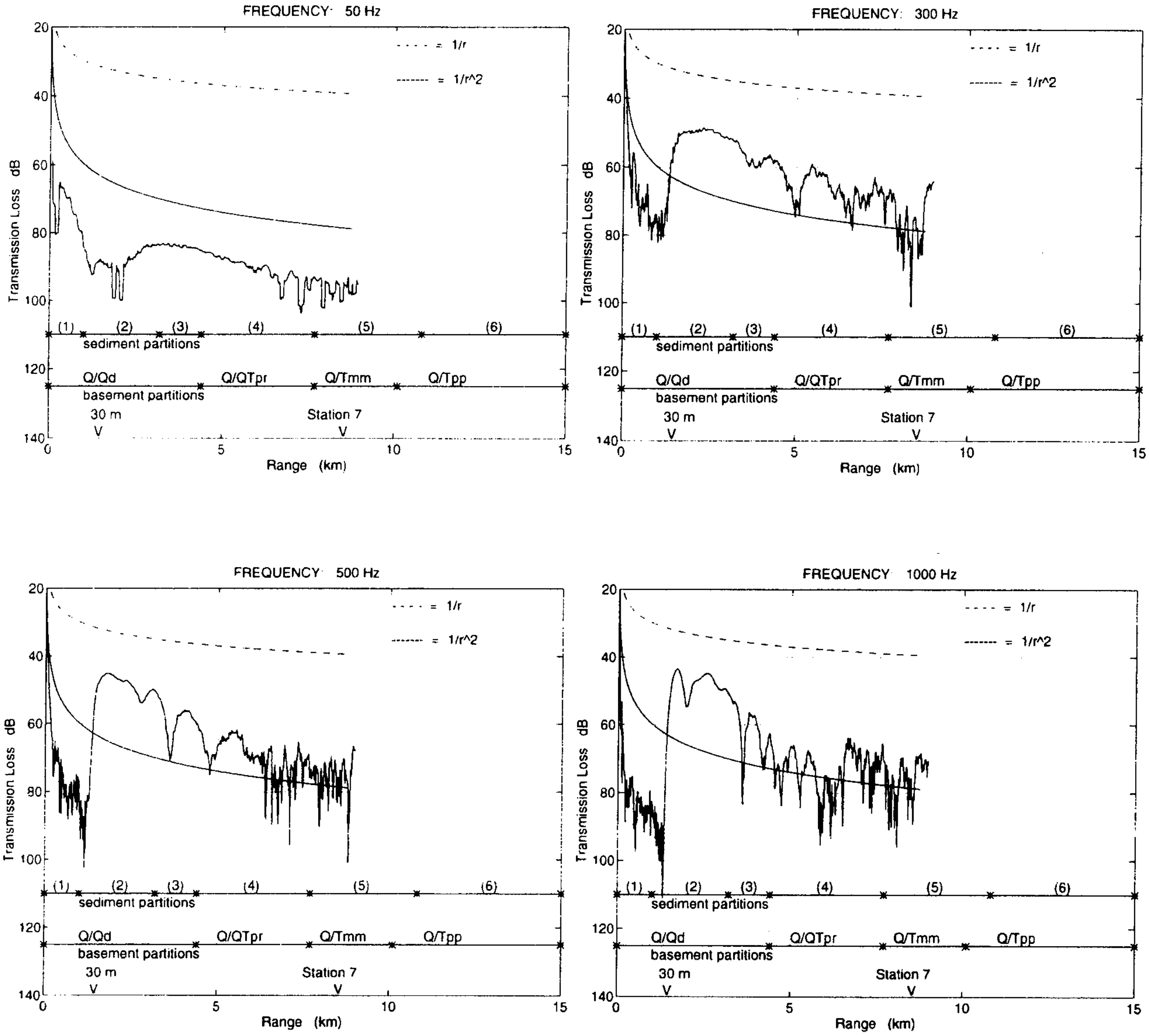

Figure 14. Transmission loss along a path from the beach 2.5 km north of Ft. Ord to Station 7 for 50, 300, 500, and 1000 Hz. Sediment types: (1) coarse sand, (2) fine sand, (3) silt, (4) clayey silt, (5) sand-silt-clay, (6) sand, muddy. (Receiver depth 30 m.)

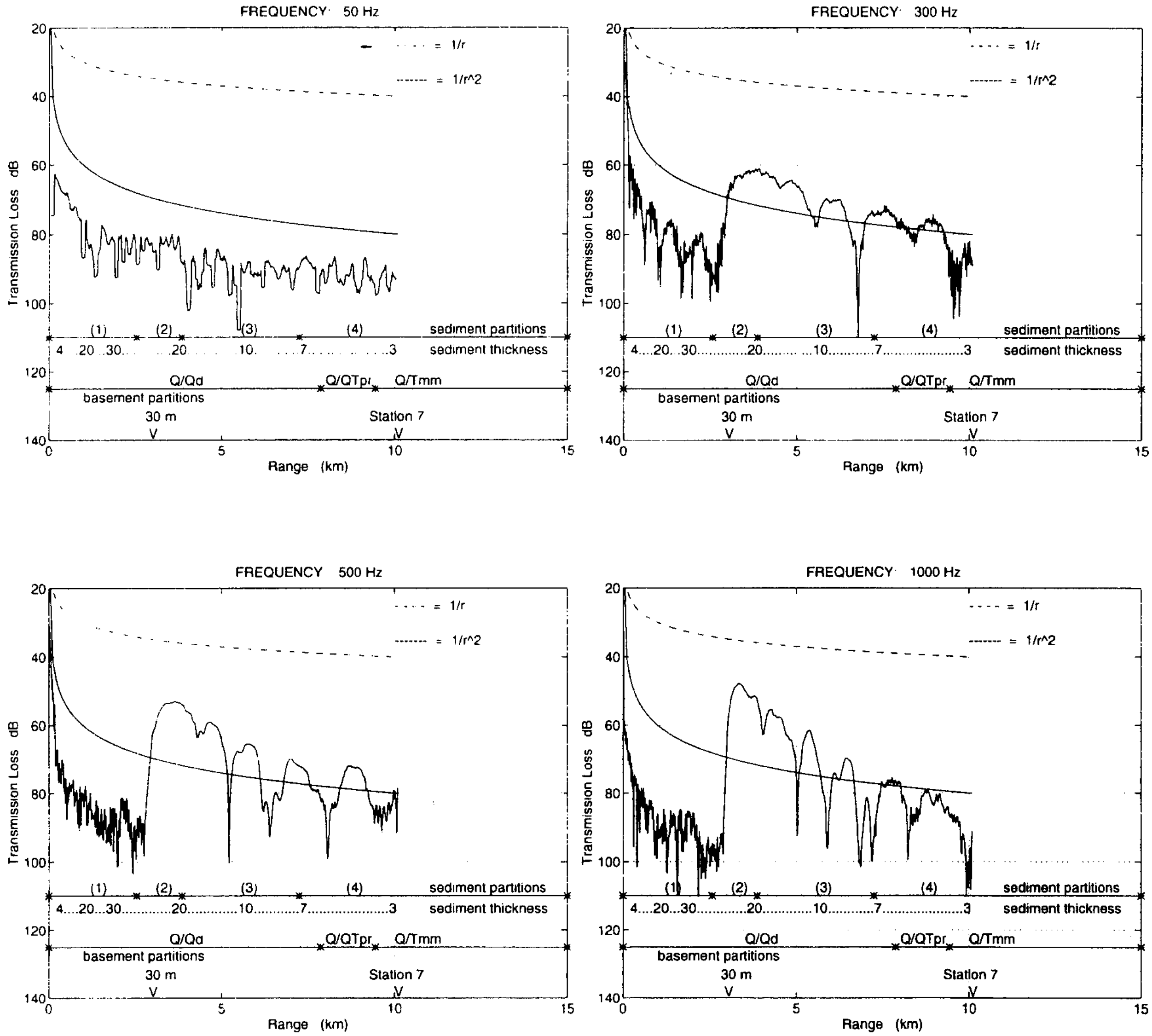

Figure 15. Transmission loss along a path from the beach 7.5 km north of Ft. Ord to Station 7 for 50, 300, 500, and 1000 Hz. Sediment types: (1) coarse sand, (2) fine sand, (3) silt, (4) clayey silt. (Receiver depth 30 m.)

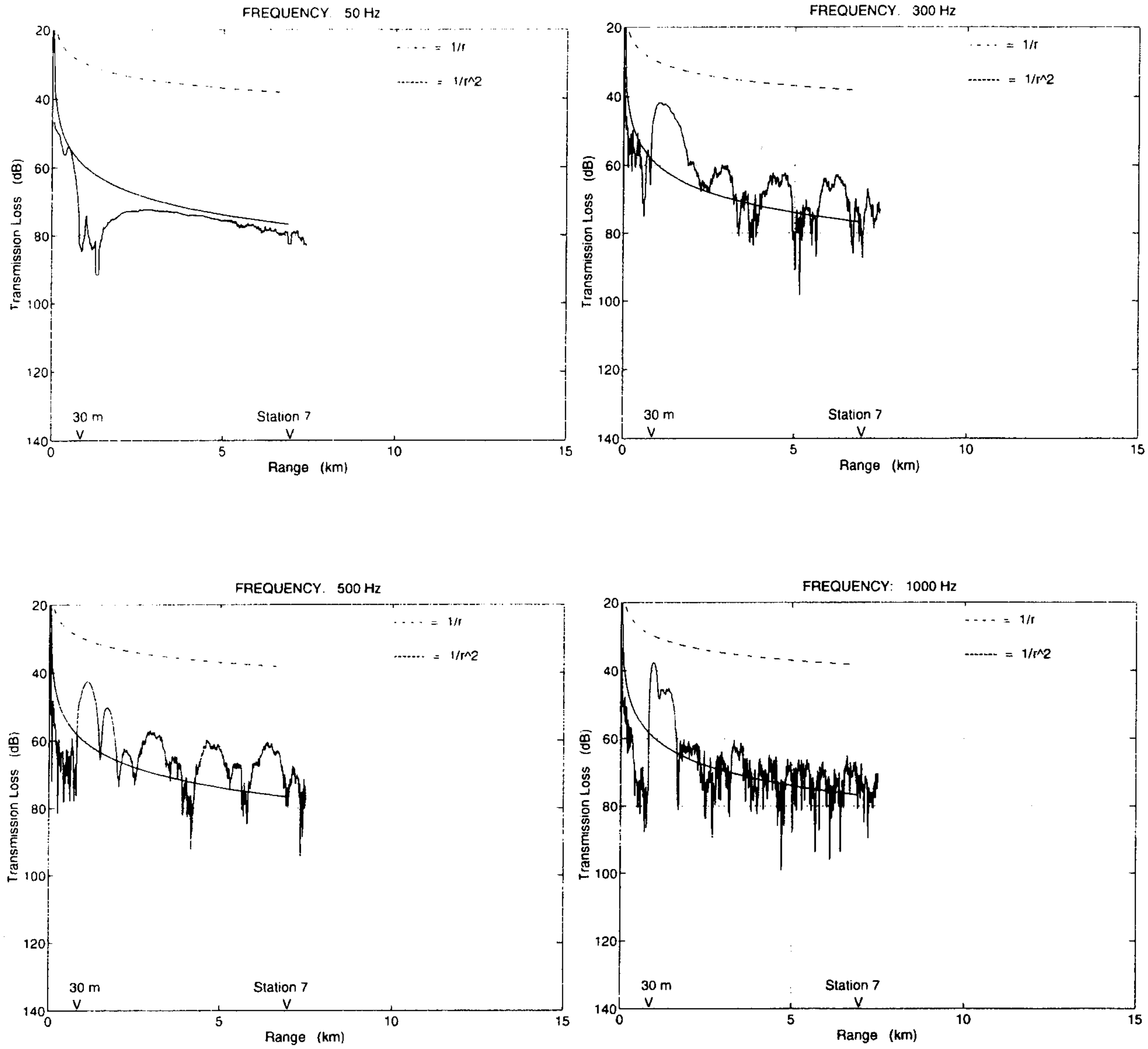

Figure 16. Transmission loss along a path from Pt. Pinos to Station 7 (uniformly granitic sea bed/no sediment). (Receiver depth 30 m.)

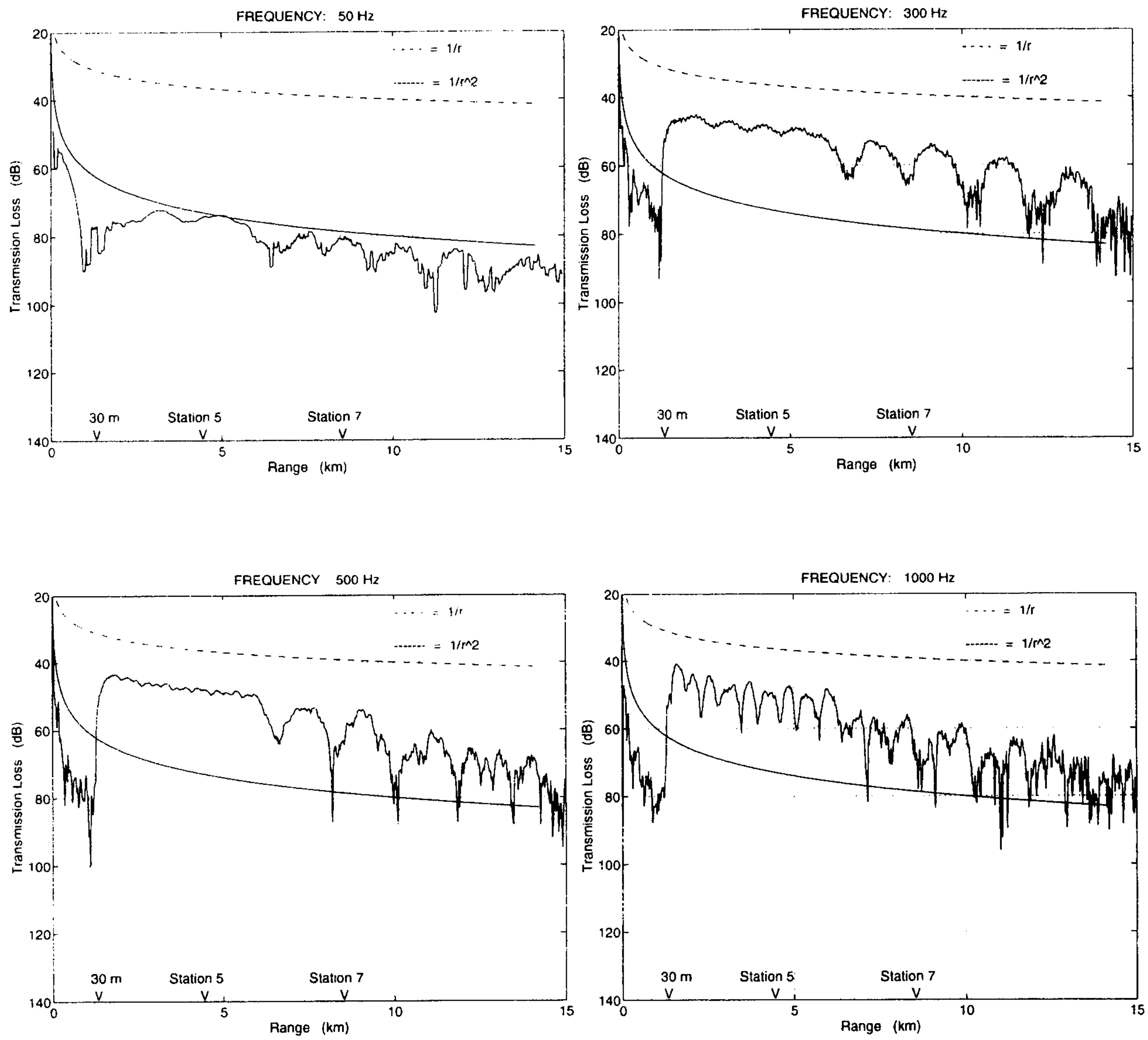

Figure 17. Transmission loss along Wilson's Line (uniformly granitic sea bed/no sediment). (Receiver depth 30 m.)

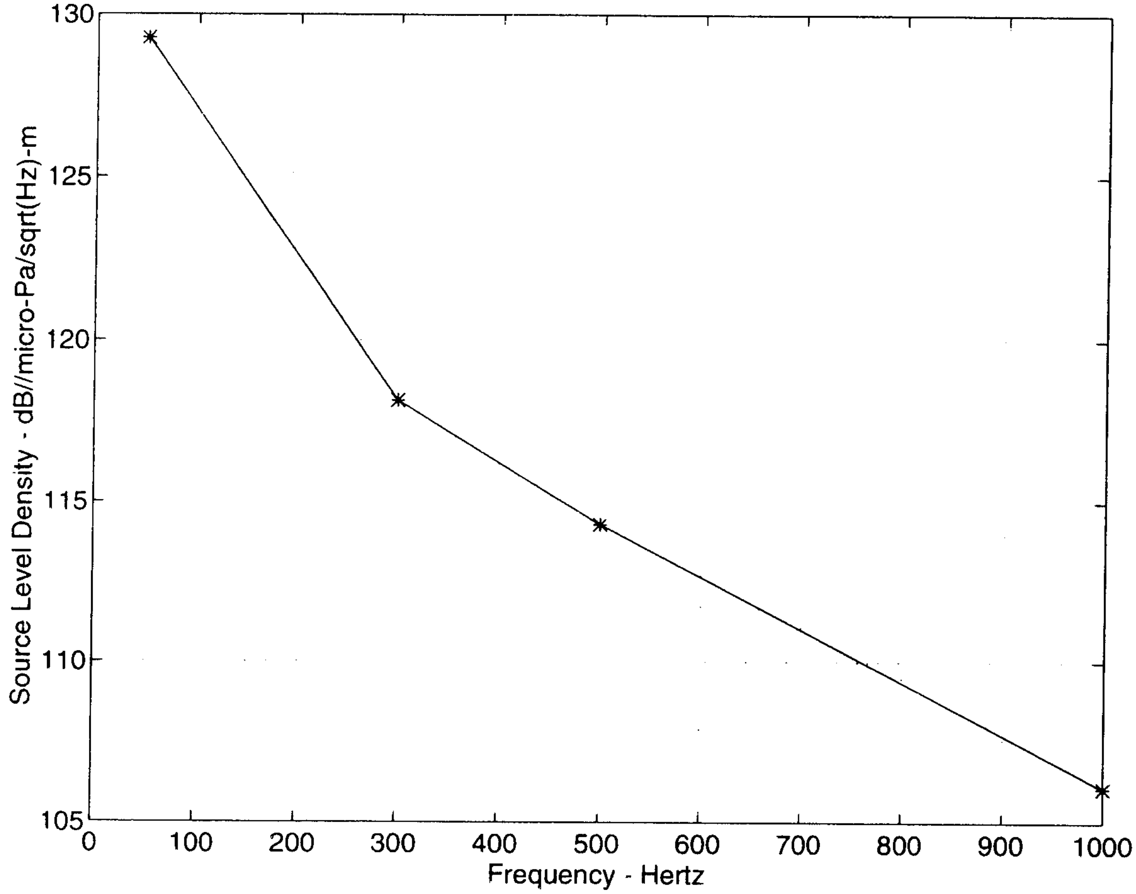

Figure 18. Heavy surf spectral source levels per meter of beach of the surf zone along the Ft. Ord beach. Determined from data at Station 7.

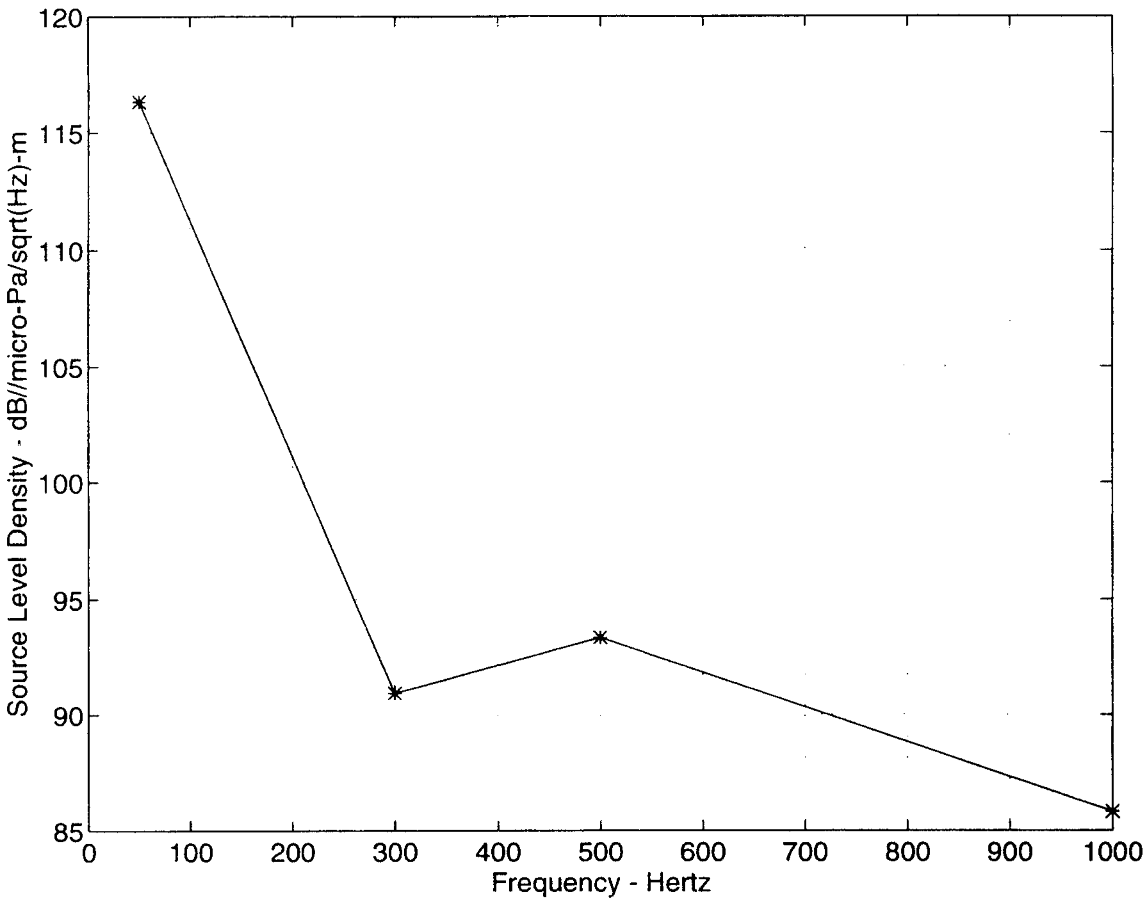

Figure 19. Light surf spectral source levels per meter of beach of the surf zone along the Ft. Ord beach. Determined from data at Station D.

V. SUMMARY AND CONCLUSION

A. SUMMARY OF RESEARCH

Omnidirectional ambient noise measurements acquired off the coast of Ft. Ord in Monterey Bay in 1980 and 1981 were applied with modelled transmission loss to make a preliminary calculation of the spectral source level per meter of beach (spectral source level density) created by surf breaking on a beach. A full geoacoustic model of the coastal environment was assembled from a suite of measured and estimated data and was used in the FEPE propagation loss model to obtain the spatial rate of energy decay as the surf-generated noise propagated seaward. A uniform 12.5 km linear effective source was assumed. Estimates of wind and wave noise were made to subtract from observed levels to determine the contribution due to surf. The source level densities for heavy surf at Ft. Ord beach were estimated to be 129 dB, 118 dB, 114 dB, and 102 dB for 50 Hz, 300 Hz, 500 Hz, and 1000 Hz respectively.

B. CONCLUSIONS

The TL results show some dependence of TL on the specific nature of the geoacoustic environment and on frequency. Results for 300 Hz show that there is about 5 dB less TL from the beach to 5 km along Wilson's Line than along a path from Pt. Pinos seaward 5 km. At 500 Hz, the TL 5 km along Wilson's Line exceeds the TL 5 km from Pt. Pinos by about 5 dB.

The TL results also show that sea bed features within a few kilometers of the beach have a greater affect on TL than more distant features. For all frequencies, TL is 10-15 dB higher along Wilson's Line with its sediment overburden (2 m thick along the entire path and in particular along the first

2-3 km) than with an artifically modelled hard, reflective bottom. No such TL difference is observed along the line between Pt. Pinos and Station 7 along which the natural sea bed is already granitic from the beach 2.5 km seaward.

The energy propagation at 50 Hz is affected by waveguide cutoff and is severely attenuated within a few kilometers of the beach. Energy at 300 Hz and 500 Hz suffers markedly less TL (20-30 dB). At 1000 Hz, the FEPE model yields less TL than probably exists due to limitations in accounting for water column absorption and bottom and surface scattering.

Pressure spectrum levels may be compared to levels due to other well known sources. The estimated 300 Hz ambient noise pressure spectrum level at Station 7 due solely to surf breaking on the Ft. Ord beach is 81 dB. At 300 Hz, the pressure spectrum level contribution of heavy shipping to deep-water ambient noise is 70 dB (Ross, 76), and the pressure spectrum level contribution of 50 kt winds is 76 dB (Wilson, 83). The estimated 500 Hz ambient noise pressure spectrum level at Station 7 due to surf breaking on the Ft. Ord beach is 78 dB. At 500 Hz, the pressure spectrum level of 50 kt winds is 74 dB.

Surf noise is estimated to account for 75-94% of the measured ambient noise intensity in Monterey Bay at 300 and 500 Hz under both high and low surf conditions.

Surf spectral source level is a transportable property which may be applied in computing ambient noise levels in other littoral regions.

C. SURF POINT NOISE

The Fort Ord beach in Monterey Bay might constitute what Navy sonarmen would classify as a "surf point noise" source. The cardioid directivity index of the sonobuoys used by Wilson et al. (85) is only 4.8 dB. The directivity index of modern towed and spherical sonar system arrays is substantially larger (>15 dB), and such systems might be affected at substantially greater ranges from the beach.

The effectiveness of Pt. Pinos as a radiating surf point noise source can only be surmised. TL estimates in Figures (11) and (12) show that acoustic energy should propagate well northeast into the bay. But since the incident waves during the experiments of Wilson et al. (85) only tangentially impacted the northern side of Pt. Pinos, it seems likely that the small amount of breaking surf energy generated there would not contribute significantly to the noise level observed in the middle of the bay. To ascertain the effectiveness of Pt. Pinos as a surf point noise source and determine its surf source level density requires measurements to be taken at sea west of the point since large waves and swell seldom arrive from the north side of the bay. Geoacoustic and TL models would then have to be developed along this path.

D. OPPORTUNITIES FOR FURTHER RESEARCH

In July 1994, an experiment similar to SWELLEX-1 was conducted by NRAD (SWELLEX-3). Essentially continuous ambient noise measurements were made from collocated vertical and horizontal line arrays in 200 m of water over a two week period. Calibrated sources were placed in the water, operated in various modes (CW and FM slide), and towed along various paths with respect to the arrays to accurately determine the spectral TL. An impulsive source was also employed to evaluate the time of arrival along different three dimensional paths. The acoustic data from these recordings will be available in the fall of 1994,(personal communication with Ryan).

In the surf zone at Duck, NC, a surf noise experiment similar to Wilson's 1980 and 1981 experiments in Monterey Bay was conducted in October 1994 by Neptune Sciences, Inc. in conjunction with numerous other surf zone experiments under the coordination of the Naval Research Laboratory, Code 7120, Washington, D. C. An initial geoacoustic model for that area has recently been assembled (Wilson and Paquin, in process). The acoustic data from this experiment will be available in winter of 1994 (personal communication with Paquin).

To confirm the transportability of surf zone source level densities to other littoral areas of strategic interest, one should first build a geoacoustic model for a particular location and determine the surf zone characteristics; second, model anticipated TL; and third, apply the appropriate source level densities, based on the surf zone characteristics of the location and the existing sea state, to compute anticipated ambient noise levels. Then one should directly measure those noise levels to verify the estimations. This approach could be taken for headland "surf point" sources as well as cuspid beach sources. Ascertaining sea bed geoacoustic properties represents the major challenge since detailed information on the nature of the sea floor sediment and sub-bottoms of the littoral environments of interest is extraordinarily scanty. Detailed bathymetry and sound speed profiles of the water column seaward from the surf zone are likewise scarce.

Measurements with calibrated directional arrays of hydrophones could provide a basis for more precise determination of surf zone source levels.

APPENDIX

A. THE SAN DIEGO BIGHT

In August 1993, the Navy Research and Development Division (NRAD) of the Navy Command, Control and Ocean Surveillance Center (NCCOSC) conducted SWELLEX-1 shoreward of the 200 m contour southwest of Point Loma. (Hodgkiss et al., 94) Recordings from 5 Hz to 750 Hz were made nearly continuously over that period from 48 hydrophones spaced uniformly on a 90 m bottom-mounted vertical array in 200 m of water. Loud broadband noise levels developed and waned over a few hours time periodically during the experiment affecting the levels at frequencies from 200 Hz to 750 Hz somewhat uniformly. Interestingly, the noise was modulated with about a 30 s period and a 5-10 dB amplitude oscillation peak to trough. Figure (20) is a lofargram showing this modulation. A bottom mounted rectangular array beneath the vertical array, installed and operated by the McDonnell-Douglas Corporation, isolated the source of the noise to the northeast quadrant which encompasses an arc from the shore of Imperial Beach 22 km away to the western side of Point Loma. This suggests that this noise is produced by breaking surf and that the modulation may have corresponded to the breaking of long-period southwest swell that was observed by scientists at sea aboard the research vessel during the experiment.

This appendix describes the assembly of the geoacoustic model for the San Diego Bight, presents the resulting TL curves from the FEPE propagation loss model program, and describes the application of processing software to recorded acoustic data from SWELLEX-1 to produce lofargrams and beamformed outputs for analysis.

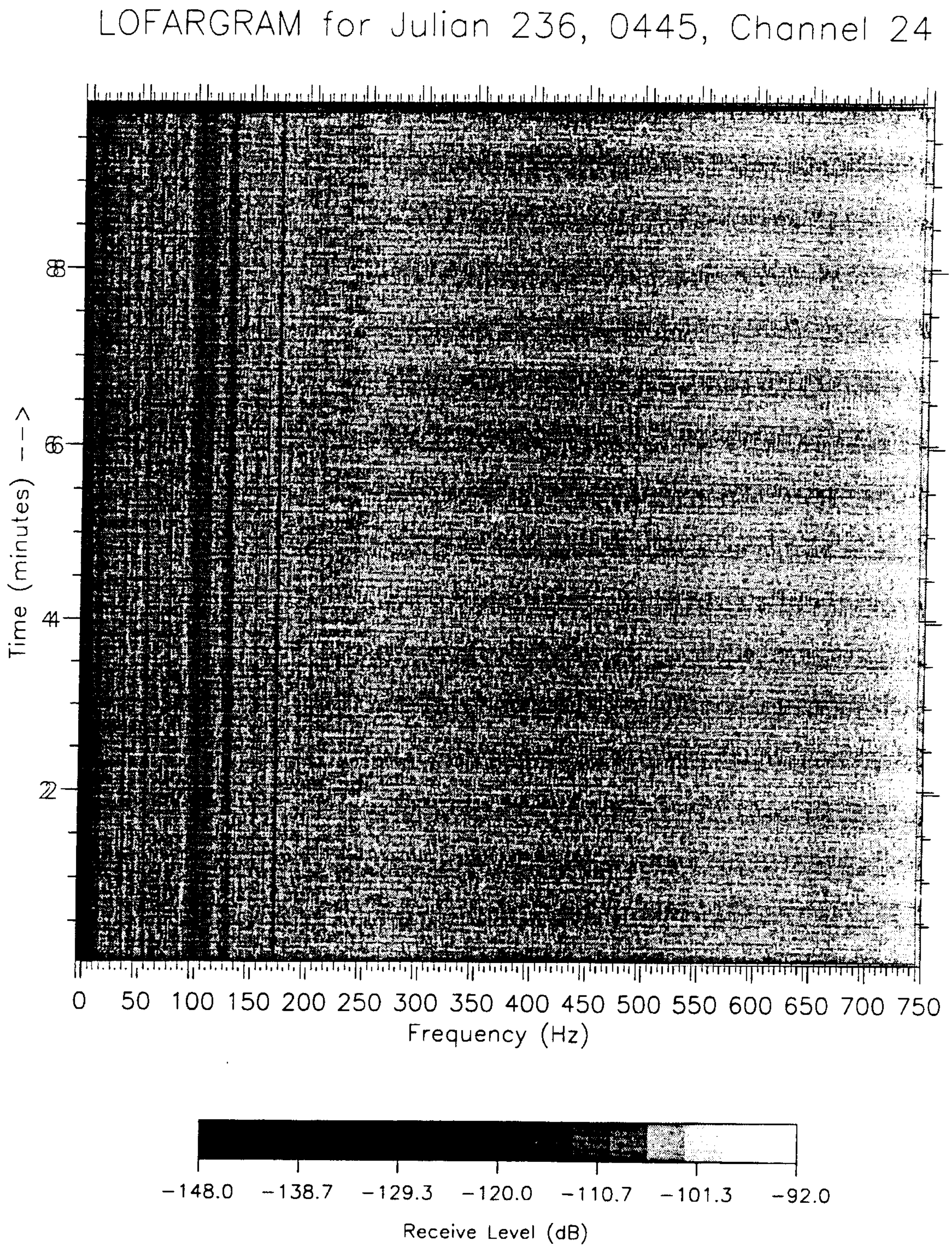

Figure 20. Lofargram depicting 30 s modulation of ambient noise recorded by hydrophone #24 of a 48 channel vertical array during SWELLEX-1 at 0445 on 23 August 1993. Gray scale reference is unknown. Relative values are of interest.

An objective in modelling TL in the San Diego Bight and analyzing SWELLEX-1 data is to identify the geographical origin of the unique, modulated noise field observed during the experiment. Another objective is to compare the modelled TL for two very different geoacoustic paths. Two possible sources of the modulated noise are Pt. Loma 13.7 km northeast of the vertical array and the Silver Strand beach 22 km east of the array. Shoal water south of Pt. Loma has been seen to cause waves to break on this promontory (author's personal observation). However, the 15 km long Silver Strand beach may be an effective source just as the long Ft. Ord beach was the source of surf noise in Monterey Bay.

For TL comparisons, two paths from the location of the vertical array employed during SWELLEX-1 were modelled. One path extended 13.7 km northeast to a point 1 km southeast of Pt. Loma and the second path extended 22 km due east to the Silver Strand just north of Imperial Beach as shown in Figure (21). Bottom profiles for these paths are shown in Figure (22).

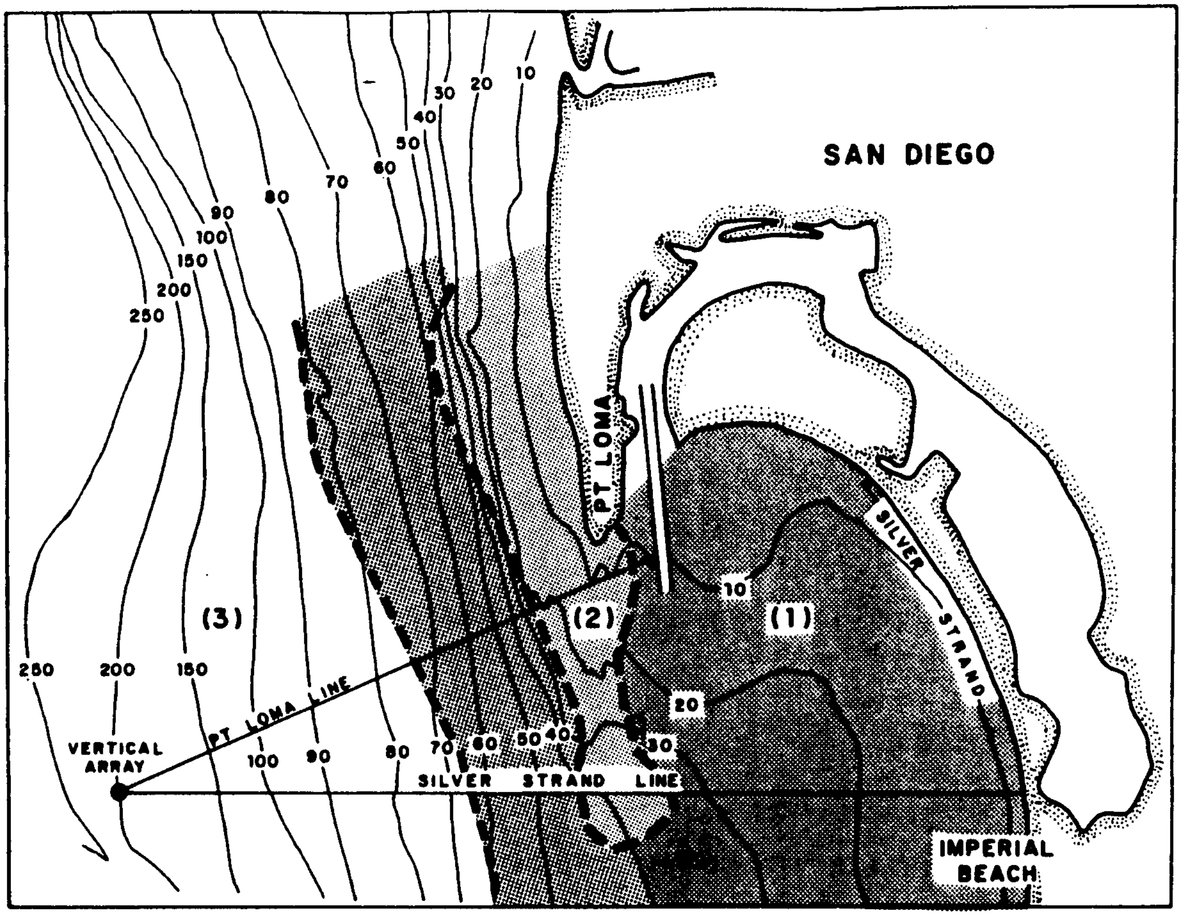

Figure 21. Paths along which propagation loss was modelled for comparison - San Diego Bight. Geoacoustic regions (from McCulloch and Greene (90)): (1) unconsolidated deposits of Quaternary age (2) undifferentiated sedimentary rocks of Late Cretaceous age, and (3) sediment and sedimentary rock of Quaternary and Tertiary (Pliocene and Miocene) age.

For San Diego, detailed water column sound speed profiles were available between water depths of 50 m and 200 m as a part of the FEPE input file used by NRAD for SWELLEX-1 (personal communication with Shook). An extrapolation was made shoreward from 50 m water depth with the assumption that the water was isospeed shoreward of the 14 m isobath due to wave mixing.

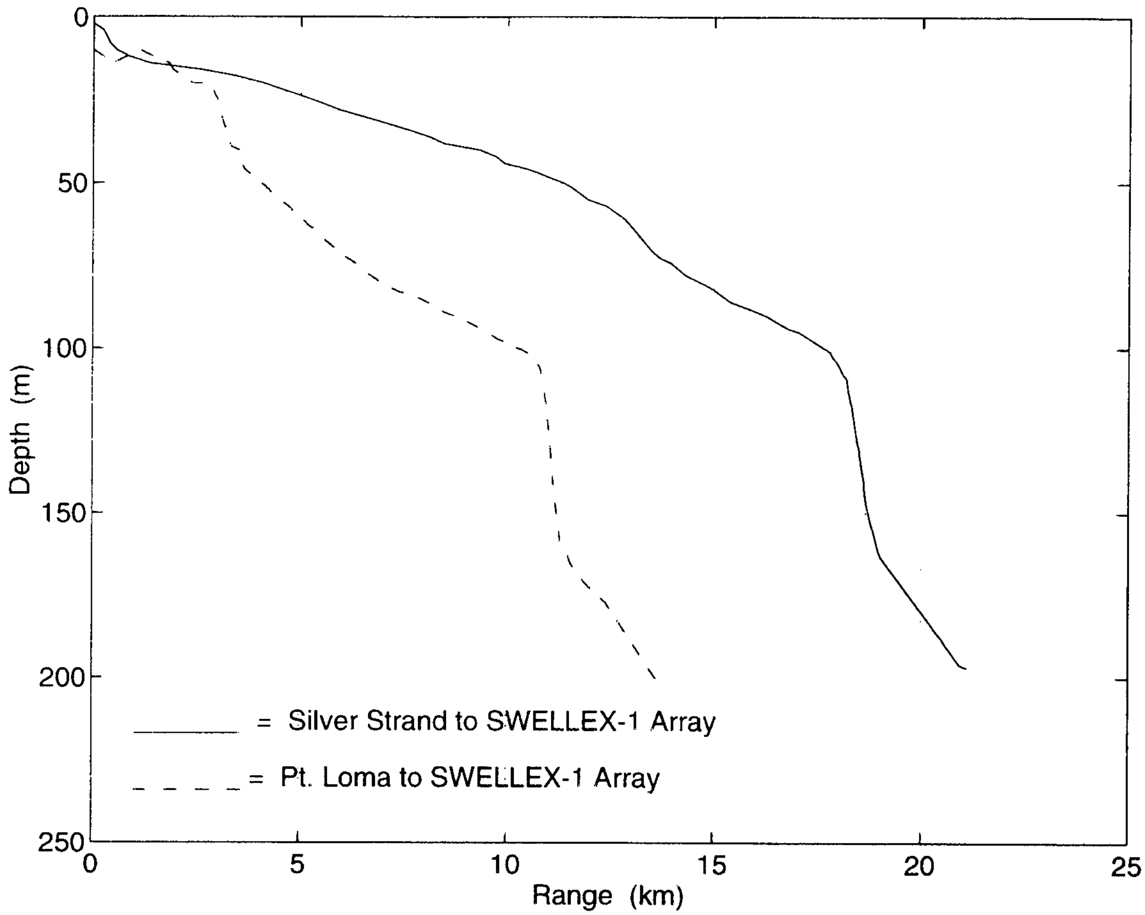

Figure 22. Bottom profiles along paths from Silver Strand and Pt. Loma to the vertical array used in SWELLEX-1.

A rapid transition from the isospeed profile was made to accommodate a steep negative sound speed gradient, a decrease of 40 m/s beneath the shallow mixed layer, in deeper water. Cold water lay beneath very much warmer surface water during SWELLEX-1. It was assumed that the gentle shelf lip along the 20 m contour impeded shoreward circulation of this heavier, colder water.

In the FEPE input file provided, NRAD modelled the sea bed in great detail vertically through the sediment deep into bedrock and horizontally from the 197 m isobath where the vertical array was located to the 50 m isobath due south of Pt. Loma. A 9.5 km north-south path was similarly modelled along the 200 m isobath north of the array. The data along this path were used in conjunction with the east-west path data to construct the geoacoustic model to Pt. Loma. Shoreward extrapolation of both of these paths was accomplished using Henry (75) for sediment thickness, McCulloch and Greene (90) and Welday and Williams (75) for sediment and sub-bottom composition, and the results of two coring samples obtained by Engineering-Science, Incorporated (94) for sediment thickness and composition. Hamilton's geoacoustic model methodology was employed to define the range-dependent geoacoustic model for input into the FEPE model.

B. TL RESULTS AND DISCUSSION

Figures (23) and (24) show filtered TL results for the Silver Strand and Pt. Loma paths respectively in the San Diego Bight. For this geoacoustic environment, which was modelled with 2 m bathymetric resolution, the frequencies evaluated are 50, 300, 500, and 750 Hz.

All plots were derived from running the FEPE TL program. The modelled receiver depth was 30 m to generate reasonable TL curves seaward of the surf zone. FEPE modelling difficulties were experienced by placing the receiver at 150 m, the mid-array depth during SWELLEX-1 (Section III.F.).

Each plot displays the basement geoacoustic regions, after McCulloch and Greene (90), a legend for which appears in Table (5). Figure (21) depicts a geographical representation of these regions in the San Diego Bight. The plots depict the sediment thickness in meters near the bottom of each plot. Also shown along the abscissa of the charts is the range of the 30 m contour, at which point the modelled receiver enters the water column (see Section III.F.), continental shelf location, and array location where appropriate.

The TL results again show that TL is dependent upon the geoacoustic environment. As was the case for Monterey Bay, the TL at 50 Hz is large and the sound energy does not propagate due to the effects of wave guide cutoff. The TL from Silver Strand out to around 13 km is roughly 50 dB or less showing excellent propagation potential of this shoreward environment. However, TL increases dramatically over the remaining 9 km to the SWELLEX-1 vertical array for frequencies above 50 Hz. Along the path from Pt. Loma, TL increases to about 70 dB at 11 km from the beach, showing less favorable propagation at all frequencies than the path from Silver Strand. The TL then increases further, by more than 20 dB, over thick (59 m) sediment but rebounds such that 13 km from Pt. Loma, the TL is the same as it is for the point 13 km from Silver Strand. TL estimates thus show 20-25 dB less TL to the array from Pt. Loma than from Silver Strand.

If the effective source length at Pt. Loma is estimated to be 1 km compared to the 15 km length of the Silver Strand beach, it can be seen that a ten-fold increase in source length alone cannot overcome the 20-25 dB difference in TL between the two paths. This analysis supports the likelihood that waves breaking off Pt. Loma were the source of the 30 s modulated noise during SWELLEX-1.

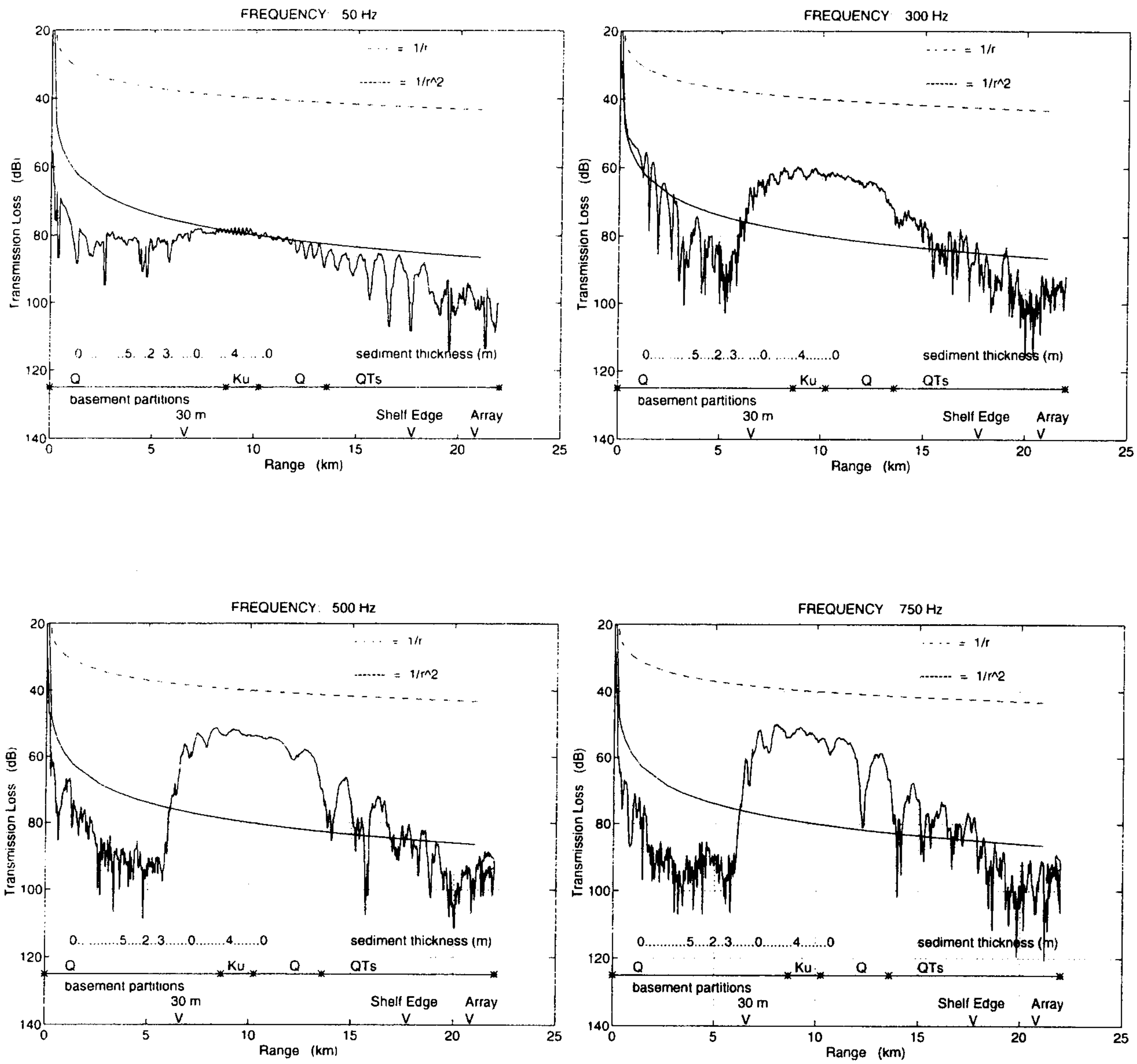

Figure 23. Transmission loss curves along a path from Silver Strand to the SWELLEX-1 vertical array for 50, 300, 500, and 750 Hz. The distance to the array and to the shelf edge are noted as is the range at which the water depth deepens to 30 m, the modelled receiver depth. Cylindrical (1/r) and spherical ($1/r^2$) spreading TL curves are shown for comparison.

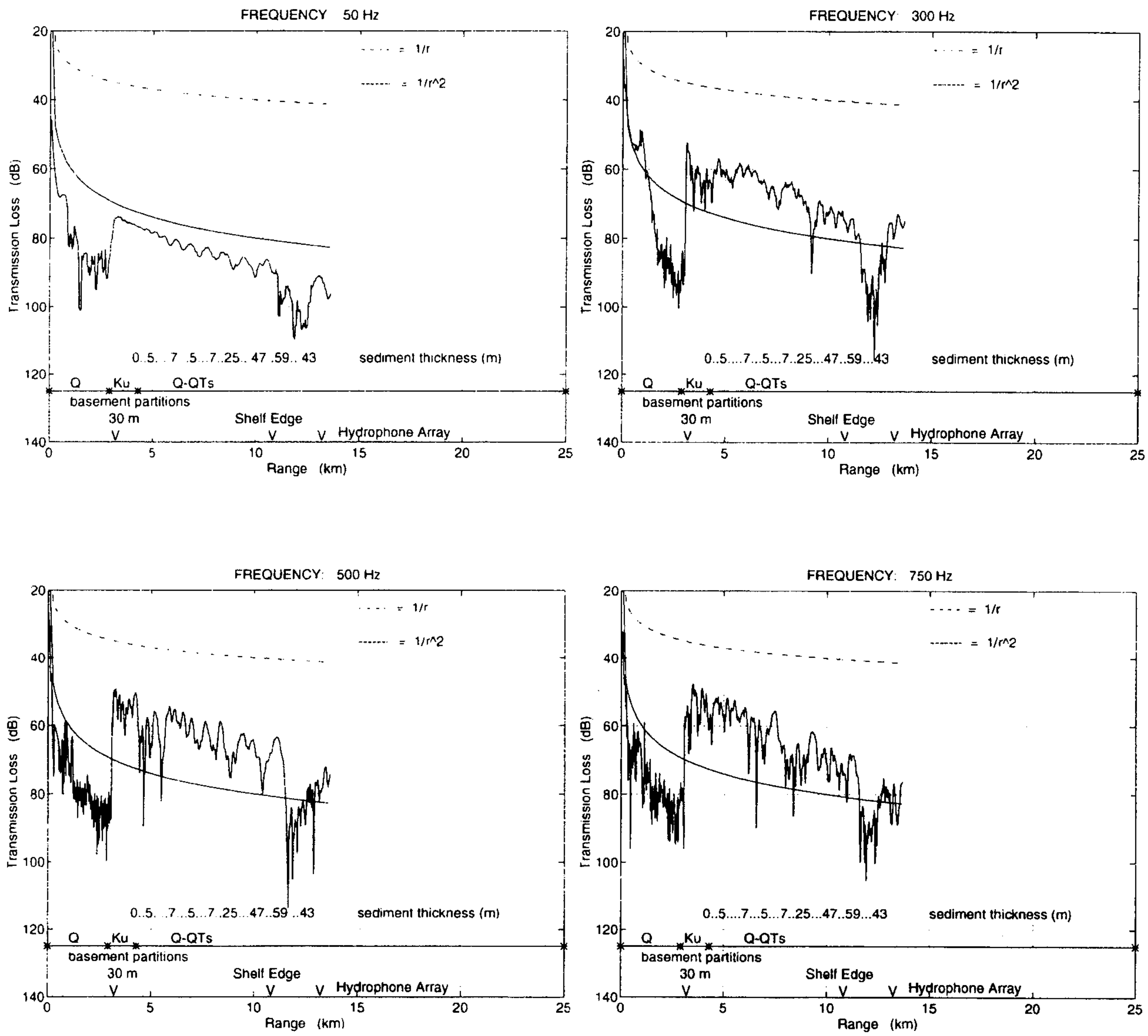

Figure 24. Transmission loss curves along a path from Pt. Loma to the SWELLEX-1 vertical array for 50, 300, 500, and 750 Hz. (Receiver depth 30 m.)

Abbrev.	Region	Description
Q	1	unconsolidated deposits of Quaternary age
Ku	2	undifferentiated sedimentary rocks of Late Cretaceous age
QTs	3	sediment and sedimentary rock of Quaternary and Tertiary (Pliocene and Miocene) age

Table 5. Legend of geoacoustic regions - San Diego Bight - from McCulloch and Greene (90). (Region numbers correspond to Figure (21))

C. SWELLEX-1 RECORDED ACOUSTIC DATA ANALYSIS

Eight millimeter (8 mm) Exabite tape recordings in TAR (tape archived) format were prepared by scientists at NRAD for data analysis (personal communication with Ryan). These tapes contain about 3.5 hours of multiplexed noise voltage signals in a time series from a vertical array of 48 hydrophones spaced 2 m apart extending from 106 m depth to the ocean floor at 200 m. Data from a segment of specified duration, normally 10 minutes, on the tape was transcribed into a standard input-output (SIO) file using a UNIX program, "scr.getnoise." A fast Fourier transform program, "scr.fft," was then used to manipulate the SIO data into 48 ".fft" files from which individual channel lofargrams were generated from 5 Hz to 750 Hz using the PV WAVE^R programs "gram.pro" and "label.pro." The 48 ".fft" files were also manipulated with UNIX program "scr.precsm" and the PV WAVE^R program "mkcsm.pro" to form a cross spectral (or covariance) matrix file for each frequency of interest which was then operated on by "bf.pro" to produce beamformed output levels of the array. (Personal communication with Shook).

The lofargram and beamform output plots permit analysis of the data to determine the time variation of the omnidirectional ambient noise level and the depression/elevation angle of the noise field. Loud modulated noise levels were observed periodically during SWELLEX-1. By evaluating appropriate segments of five Exabite tapes covering five different three and a half hour periods on two different days, and correlating the results with tidal, weather, and swell conditions, it may be possible to show that the source of the noise field is indeed breaking waves in the surf zone. Azimuthal directivity of the noise field unfortunately cannot be accurately evaluated for SWELLEX-1 due to difficulties encountered in the installation of the horizontal array.

By comparing the time of appearance of the modulated noise with tidal fluctuations during a given day, it may be possible to correlate that the modulated noise field develops during low tides. As the tide ebbs, water south of Pt. Loma becomes shallow enough to cause waves to break (author's personal observation). Long-period swell reported during SWELLEX-1 by scientists at sea (personal communication with Ryan) might also break in this shoal water and cause the 30 s modulated surf-generated noise.

Examination of the beamformed data may confirm that the source of the modulated noised is distant from the array; i.e., if the noise affects near-broadside beams of a vertical array substantially more than it affects beams toward endfire, the arrival path is largely horizontal which tends to confirm that the source is distant.

Combining analyses of TL in the San Diego Bight and the lofargram and beamform analysis from the preceding paragraphs, may allow one to distinguish the source of the noise as waves breaking south of Pt. Loma or waves breaking along the Silver distinguish the source of the noise as waves breaking south of Pt. Loma or waves breaking along the Silver Strand beach.

D. SWELLEX-1 ANALYSIS RESULTS

Figure (25) depicts tidal variations and Figure (26) depicts wind conditions taken by the National Weather Station at the San Diego airport (personal communications with W. Cegiel) on 17 and 23 August 1993, the two days on which recorded acoustical data was analyzed. Table (6) shows the fifteen specific ten minute time periods during those days over which lofargrams were developed. Lofargrams identified by an asterisk appear as Figures (27)-(30). Table (6) also identifies which lofargrams displayed the 30 s modulation (+) and which did not (-). Figures (27) and (29) are examples of lofargrams that displayed the modulated noise on 17 and 23 August respectively. Figures (28) and (30) are examples of lofargrams that displayed no modulated noise on those two days.

There is not a strong correlation between the presence of the noise pattern and low tide condition. On 17 August, the 0130 gram shows no modulated noise but rather several loud random noisy events of 15-20 s duration. This gram represents ambient noise conditions roughly 1.25 hr before low tide during which one would have expected the modulated surf noise to be present. Sea level was about 1 ft below mean lower low water (MLLW). The four grams that follow, hourly through 0530, all display the modulated noise pattern. 0530 corresponds to a tidal height of about 2.5 ft above MLLW. However, grams made at 1345 and 1515 on the same day, during which sea level was less than 2 ft above MLLW, showed no sign of the modulated noise, contrary to what one would have expected had the swell still been present in the afternoon.

low tide on 23 August. Sea level was between 2.5 and 3.5 ft above MLLW during this period, higher than the tide above which the modulated noise had ceased on 17 August. It is possible that the swell was larger on 23 August. Interestingly, the modulation periodicity of the 0615 gram shifted to about 90 s.

Wind speed data for 17 and 23 August support the existence of rather light local wind generated surf on both days. As seen in Figure (26) the peak recorded wind speed was 12 kts on 17 August and 9 kts on 23 August. The average wind speed on those two days was only 5-6 kts.

Data from the National Data Buoy Center, Stennis Space Center, Mississippi were reviewed for four buoys off the California coast during the periods in question. None of these buoys recorded any significant wave energy activity on 17 or 23 August in the vicinity of 0.03 Hz (corresponds to a wave period of 30 s). Only if wave energy at that very low frequency were substantial would the buoys have detected it. That the scientists conducting SWELLEX-1 observed large swell does not conflict with the lack of recorded wave energy at 0.03 Hz. (Personal communication with K. Steele).

Figure (31) shows the beamformed output of all 48 hydrophones taken at 0435 on 17 August at 300 Hz. This indicates that a primary arrival path of the noise levels that appeared on the lofargrams was approximately horizontal.

Without more careful assessment of actual wave activity on Pt. Loma and Silver Strand beach during SWELLEX-1, it is not possible to confirm that the 30 s period noise was due to swell breaking on the beach. However, TL considerations tend to suggest that the specific source of the noise was breaking waves south of Pt. Loma.

	17 August - TAR Tape 07	17 August - TAR Tape 08	17 August - TAR Tape 11
Time interval	0130-0140	0435-0445*	1345-1355
Noise present	-	+	-
Time interval	0230-0240	0530-0540	1515-1525
Noise present	+	+	-
Time interval	0330-0340	0700-0710*	1645-1655
Noise present	+	-	-

	23 August - TAR Tape 52	23 August - TAR Tape 55
Time interval	0315-0325*	1330-1340
Noise present	+	-
Time interval	0445-0455**	1500-1510*
Noise present	+	-
Time interval	0615-0626	1620-1630
Noise present	+ (90 s)	-

Table 6. Lofargrams identifying the presence or non-existence of the modulated noise pattern observed during SWELLEX-1. *See Figures (27)-(30). **See Figure (20).

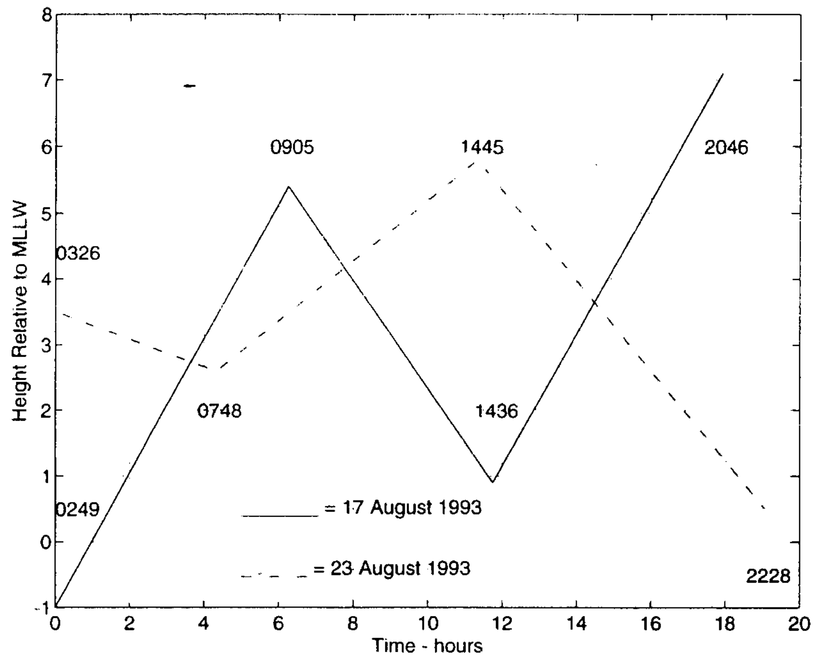

Figure 25. Tidal variations for 17 and 23 August 1993.

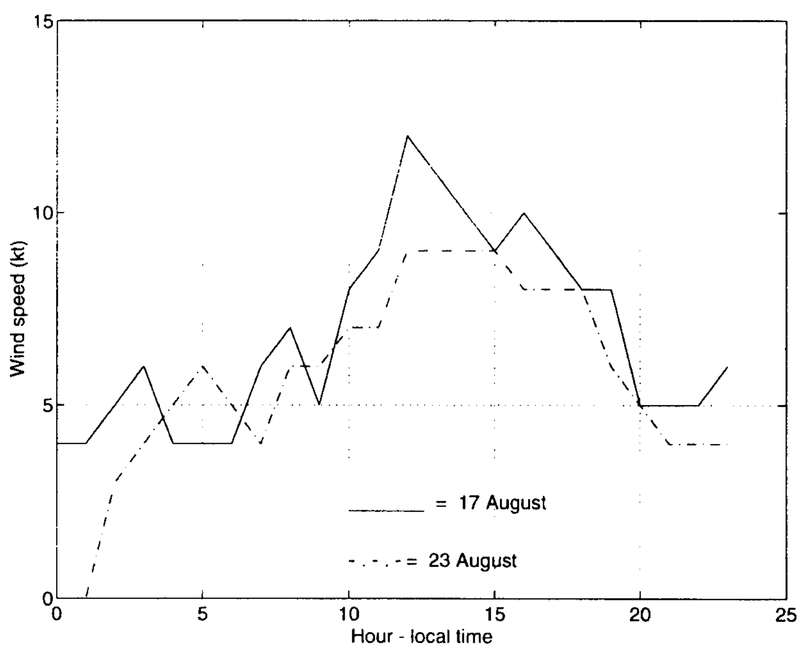

Figure 26. Wind speeds for 17 and 23 August 1993.

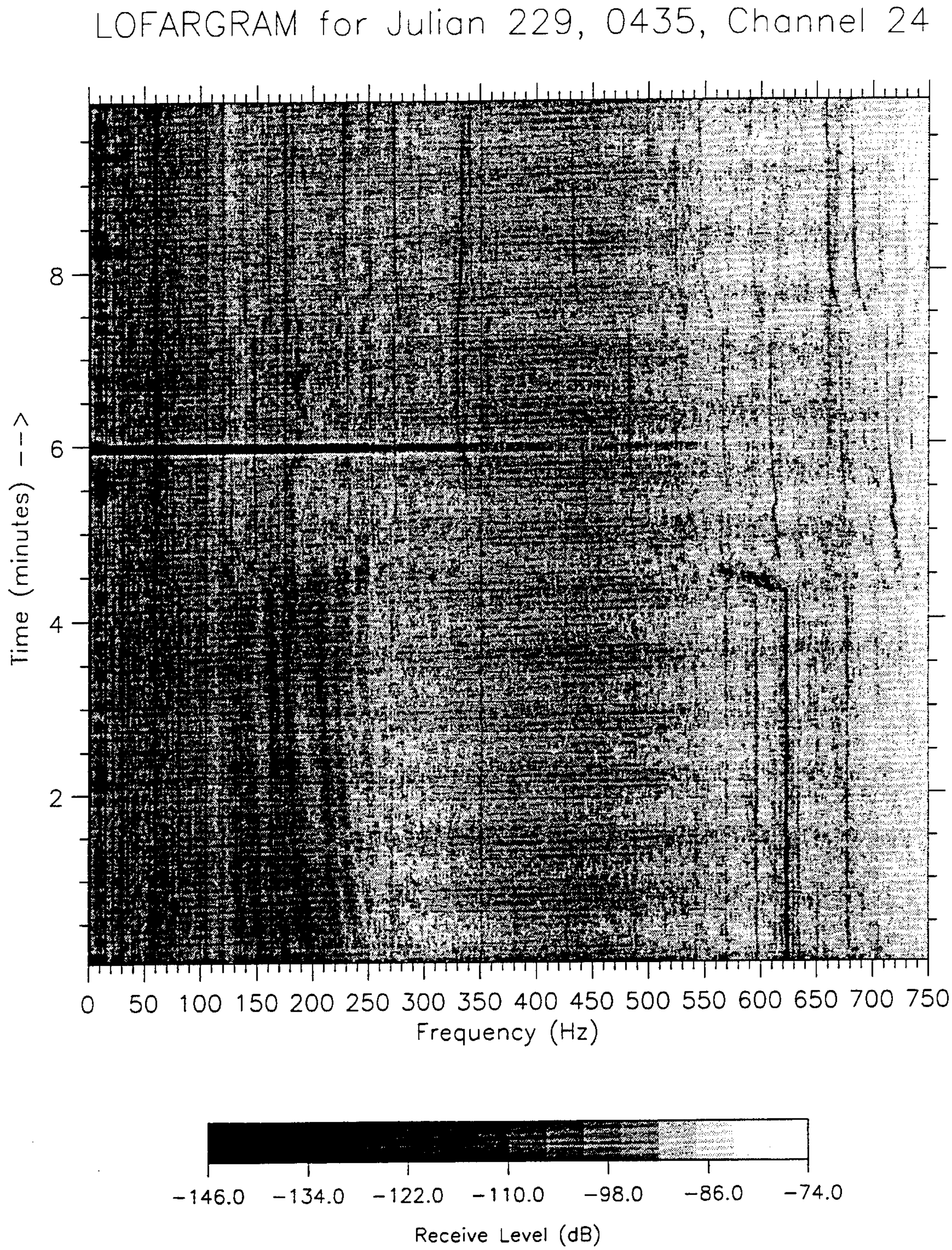

Figure 27. 1-750 Hz lofargram for 0435 to 0445 on 17 August 1993 showing evidence of 30 s period noise modulation. Gray scale reference is unknown. Relative values are of interest.

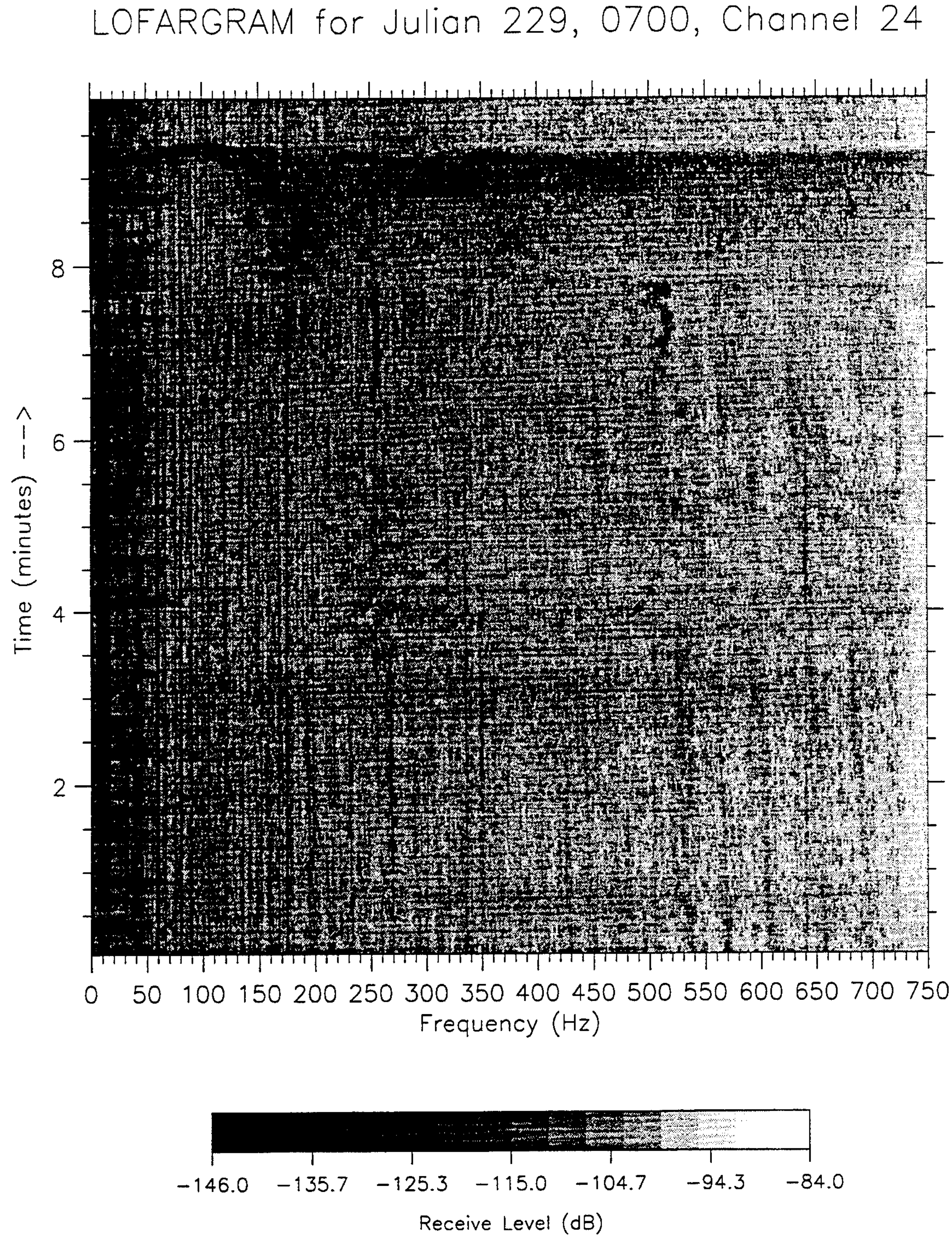

Figure 28. 1-750 Hz lofargram for 0700 to 0710 on 17 August 1993 showing no evidence of 30 s period noise modulation.Gray scale reference is unknown. Relative values are of interest.

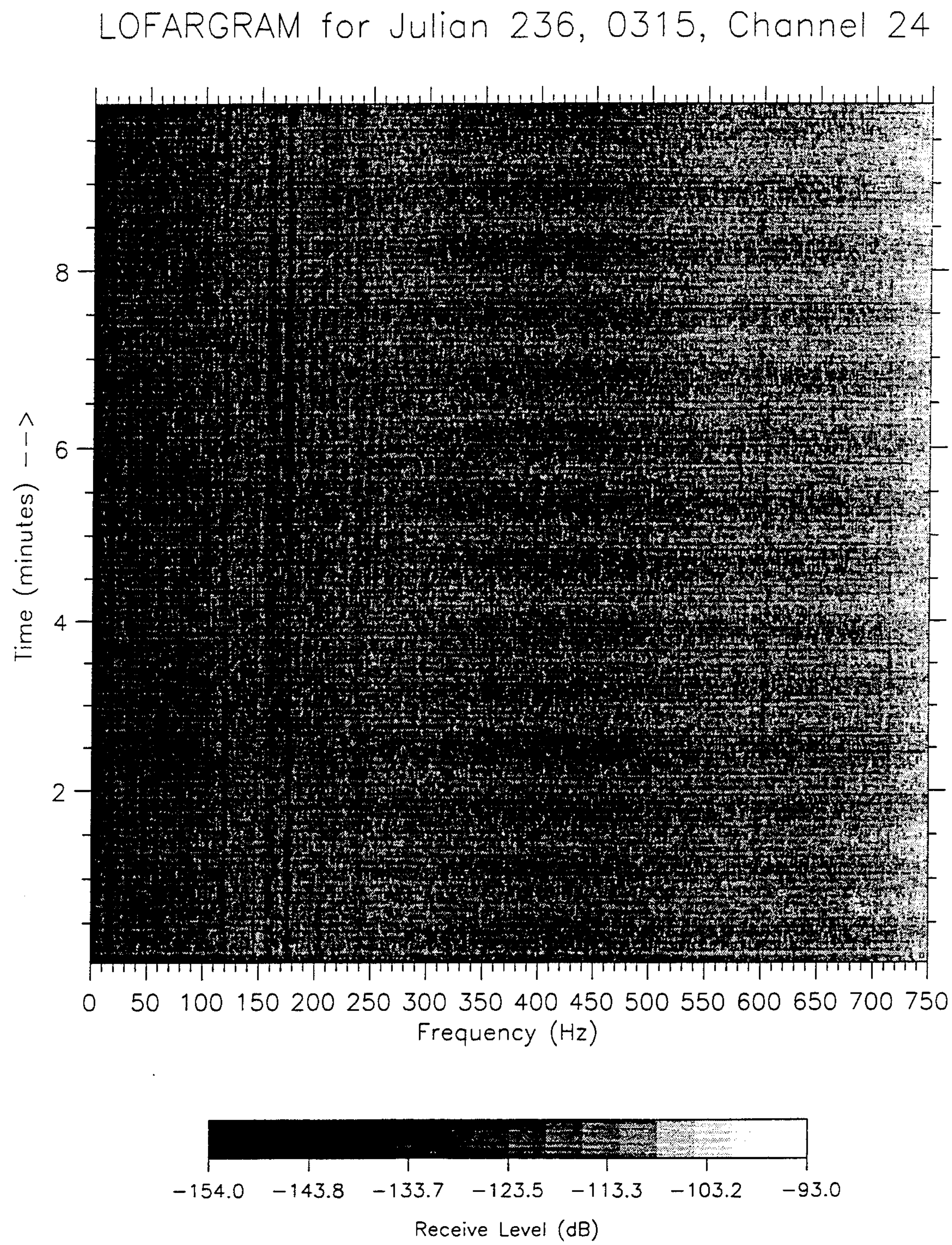

Figure 29. 1-750 Hz lofargram for 0315 to 0325 on 23 August 1993 showing evidence of 30 s period noise modulation. Gray scale reference is unknown. Relative values are of interest.

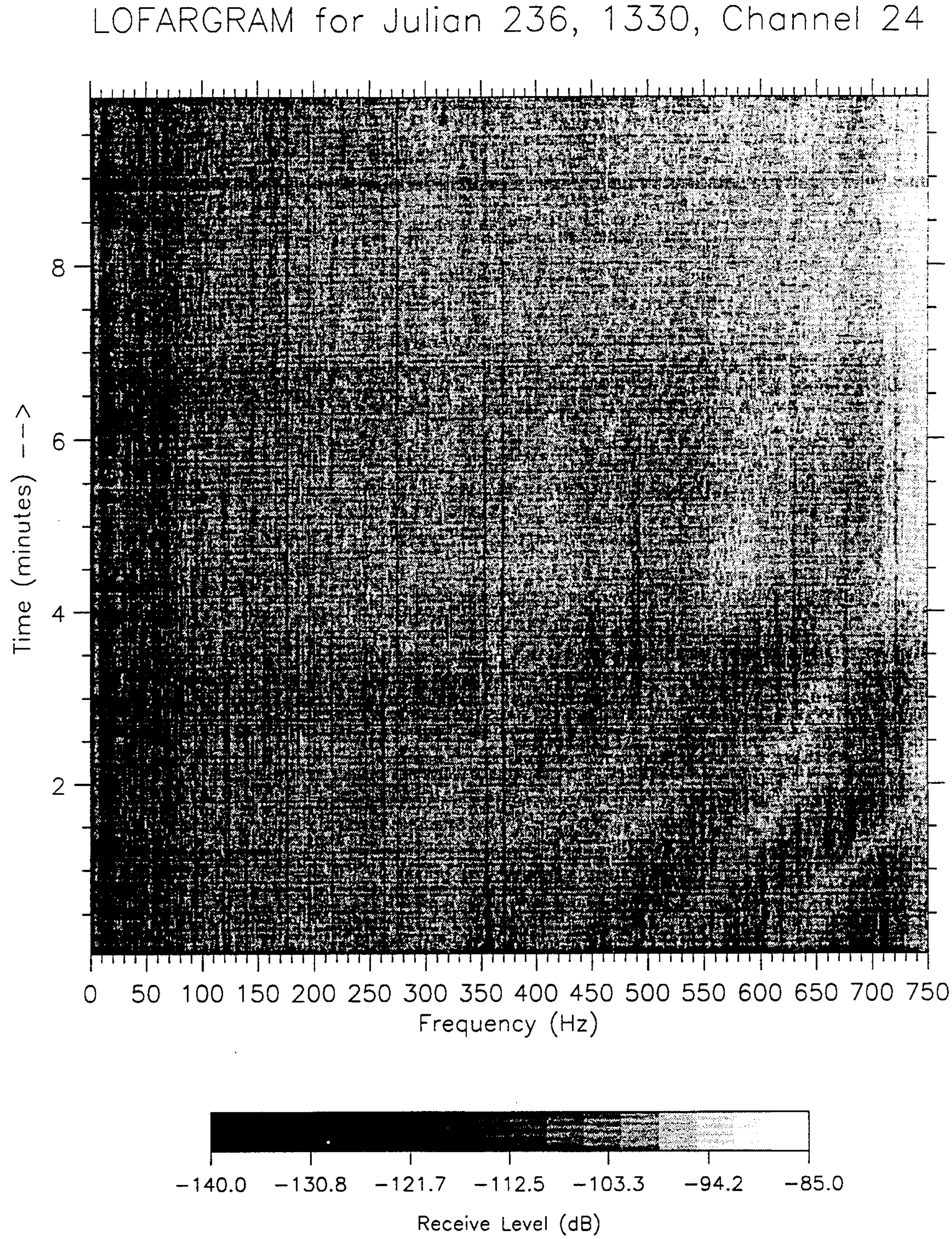

Figure 30. 1-750 Hz lofargram for 1330 to 1340 on 17 August 1993 showing no evidence of 30 s period noise modulation. Gray scale reference is unknown. Relative values are of interest.

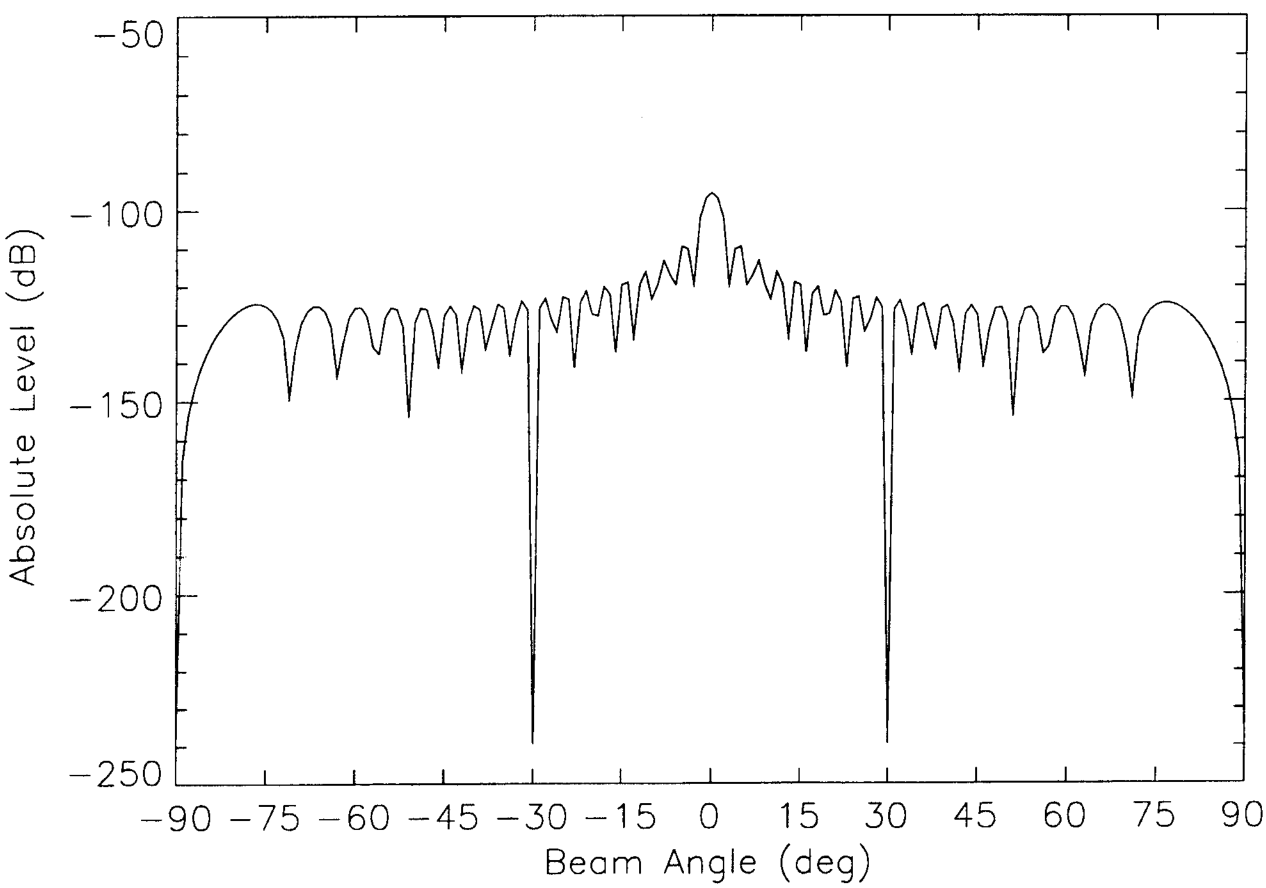

Figure 31. Beamformed output from the vertical array for 300 Hz at 0435 on 17 August 1993. Vertical scale reference is unknown. Relative values are of interest.

LIST OF REFERENCES

Bardyshev, V. I., and N. G. Kozehelapova, and V. I. Kryshnii, "Study of Underwater Noise Distributions in Inland Sea and Coastal Regions," *Akust. Zh.* 19, (129-132) (March-April 1973) [English Transl., *Soviet Physical Acoustics*, 19, (95-96), 1973].

Bieda, G. E., *Measurement of the Viscoelastic and Related Mass-Physical Properties of Some Continental Terrace Sediments*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 1970.

Carey, W. M. and J. W. Fitzgerald, "Low Frequency Noise From Breaking Waves," in *Natural Physical Sources of Underwater Sound, Sea Surface Sound (2)*, B. R. Kerman editor, Kluwer Academic Publishers, Boston, Massachusetts, 1993.

Chase, T. E., *Marine Topography of the Monterey Bay Region* (draft), U. S. Geological Survey, Menlo Park, California, 1993.

Chin, J. L. and H. E. Clifton and H. T. Mullins, "Seismic Stratigraphy and Late Quaternary Shelf History, South-Central Monterey Bay, California," *Marine Geology*, 81 (135-157), 1988.

Personal Communications between W. Cegiel, National Weather Service, San Diego, California and the author, 6 October 1994.

Collins, M. D., "FEPE User's Guide," Technical Note 365, Naval Ocean Research and Development Activity, Stennis Space Center, Mississippi, 1988.

Elles, C. J., *Analysis of Acoustic Ambient Noise in Monterey Bay, California*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 1982.

Engineering-Science, Incorporated, *Tijuana Oceanographic Engineering Study for the South Bay Ocean Outfall for the City of San Diego, California*, 1994.

Guza, R. T. and E. B. Thornton, "Observations of Surf Beat," *Journal of Geophysical Research*, 90, (C-2) (3101), 1985.

Hamilton, E. L., "Geoacoustic Modelling of the Sea Floor," *Journal of the Acoustical Society of America*, 68 (5) (1313-1340), 1980.

Hamilton, E. L., "Vp/Vs and Poisson's Ratios in Marine Sediments and Rocks," *Journal of the Acoustical Society of America*, 66 (1582-1589), 1979.

Hamilton, E. L., "Sound Velocity-Density Relations in Sea Floor Sediments and Rocks," *Journal of the Acoustical Society of America*, **63** (2) (366-377), 1978.

Henry, M. J., *The Unconsolidated Sediment Distribution on the San Diego County Mainland Shelf*, Master's Thesis, San Diego State University, La Jolla, California, 1975.

Hodgkiss, W. S. and G. L. D'Spain and A. M. Richardson, "Ambient Noise Vertical and Horizontal Directionality During SWELLEX-1," 127th Meeting, Acoustical Society of America, Boston Massachusetts, June 1994.

Hollett, R. D., "Observations of Underwater Sound at Frequencies Below 1500 Hz From Breaking Waves at Sea," *Journal of the Acoustical Society of America*, **95** (1), 1994.

Kennedy, R. M. and S. A. L. Glegg, "Acoustic Radiation due to Wave-breaking," 123rd Meeting, Acoustical Society of America, Salt Lake City, Utah, May 1992.

Knudsen, V. O., and R. S. Alford, and J. W. Emling, "Underwater Ambient Noise," *Journal of Marine Research* vol. VII, (410-429), 1948.

Kramer, S. B., *Measurement of Viscoelastic Properties of Some Recent marine Sediments by a Torsionally Oscillating Cylinder Method*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 1973.

Loewen, M. R., "Laboratory Measurements of the Sound Generated by Breaking Waves," Doctoral Dissertation, The Massachusetts Institute of Technology, Cambridge, Massachusetts, December 1991.

McCulloch, D. S. and H. G. Greene, (editors), *Geological Map of the Central California Continental Margin*, California Continental Margin Geological map Series, State of California Resources Agency, Deptartment of Conservation, Division of Mines and Geology, 1990.

McGirr, R. and D. King, "A Review of Candidate Shallow Water Propagation Losss Models," Technical Note 346, Naval Ocean Research and Development Activity, Stennis Space Center, Mississippi, 1989.

Northrup, J., "Geoacoustic Parameters of the NOSC Tower Site," NOSC Technical Note 529, Naval Ocean Systems Center, San Diego, California, 1978.

Paliatsos, D., *Computer Studies of Sound Propagation in a Wedge-shaped Ocean with Penetrable Bottom*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 1989.

Personal Communications between J. Paquin-Fabre, Principle Investigator for Duck-94, Neptune Sciences, Slidell, Mississippi and the author, October 1994.

Richardson, M. D. and K. B. Briggs, "On the Use of Acoustic Impedance Values to Determine Sediment Properties," *Acoustic Classification and Mapping of the Sea Bed*, Institute of Acoustics, N. G. Pace and D. N. Langhorne, editors, Vol. 15, Part 2 (15-24), University of Bath, United Kingdom, 1993.

Ridlon, J. B., *Bathymetry and Structure of San Clemente Island, California, and Tectonic Implications for the Southern California Continental Borderland*, Doctoral Dissertation, Oregon State University, Corvallis, Oregon, 1970.

Ross,D., *Mechanics of Underwater Noise*, Pergamon Press, New York, New York, 1976.

Personal Communications between F. Ryan, Scientist, RDTE Division, Naval Command, Control and Ocean Surveillance Center, San Diego, California and the author, 27 May and 17 June 1994.

Various Personal Communications between F. Ryan, R. Bachman, Scientists, RDTE Division, Naval Command, Control and Ocean Surveillance Center, San Diego, California and the author, June-September 1994.

Saenger, R. A., "An Estimate of the Offshore Ambient Noise Spectrum Produced by a Pounding Surf," *Journal of the Acoustical Society of America*, 33 (1674-1675), 1961.

Various Personal Communications between L. Shook, Analyst, RDTE Division, NCCOSC, San Diego, California and the author, 30 June and July-August 1994.

Personal Communications between K. Steele, National Data Buoy Center, NOAA, Stennis Space Center, Mississippi, and the author October 1994.

Welday, E. E. and J. W. Williams, "Offshore Surficial Geology of California," Map Sheet 26, State of California Resources Agency, Deptartment of Conservation, Division of Mines and Geology, 1975.

Wenz, G. M., "Ambient Noise in the Ocean: Spectra and Sources," *Journal of the Acoustical Society of America*, 34 (1936-1948), 1962.

Wilson, J. H., "Wind Generated Noise Modelling," *Journal of the Acoustical Society of America*, 73 (1) (211-216), 1983.

Wilson, O. B., and S. M. Wolf and F. Ingenito, "Measurement of Acoustic Ambient Noise in Shallow Water due to Breaking Surf," *Journal of the Acoustical Society of America*, 78 (1) (190-195), 1985.

Zakharov, L. M., and S. M. Rezhevkin, "Phase Gradient Measurements in Sound Fields," *Akust. Zh.* 20, (393-401) (May-June 1974) [English Translation, *Soviet Physical Acoustics*, 20, (242-245), 1974].

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